Graphite from Lignite

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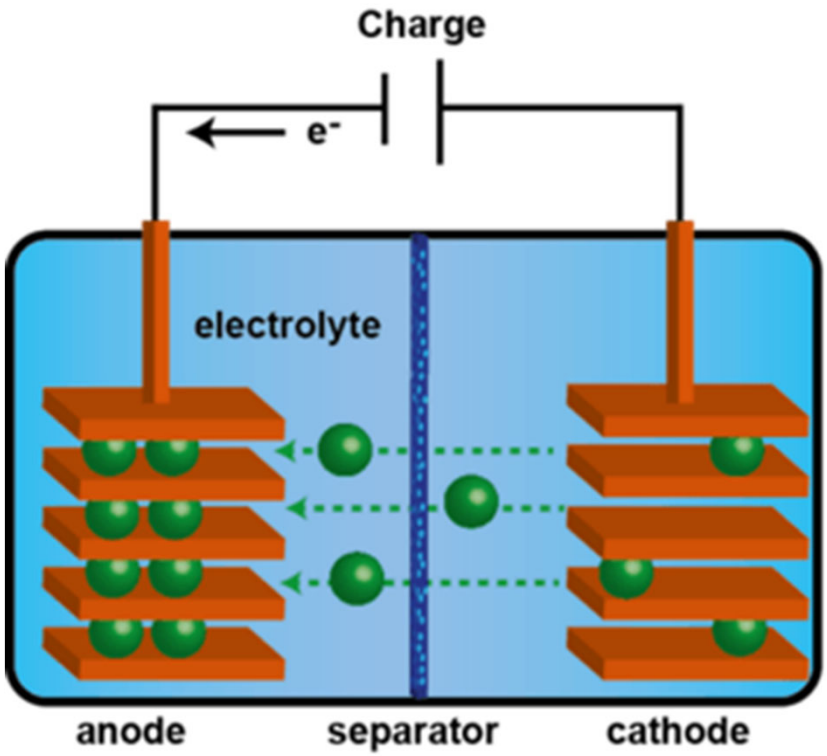
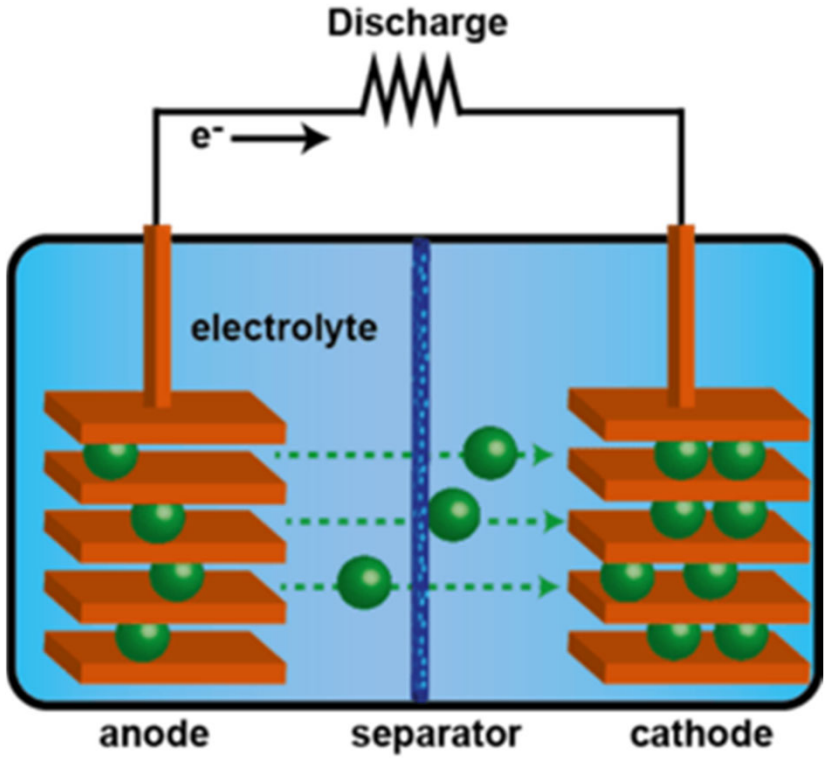
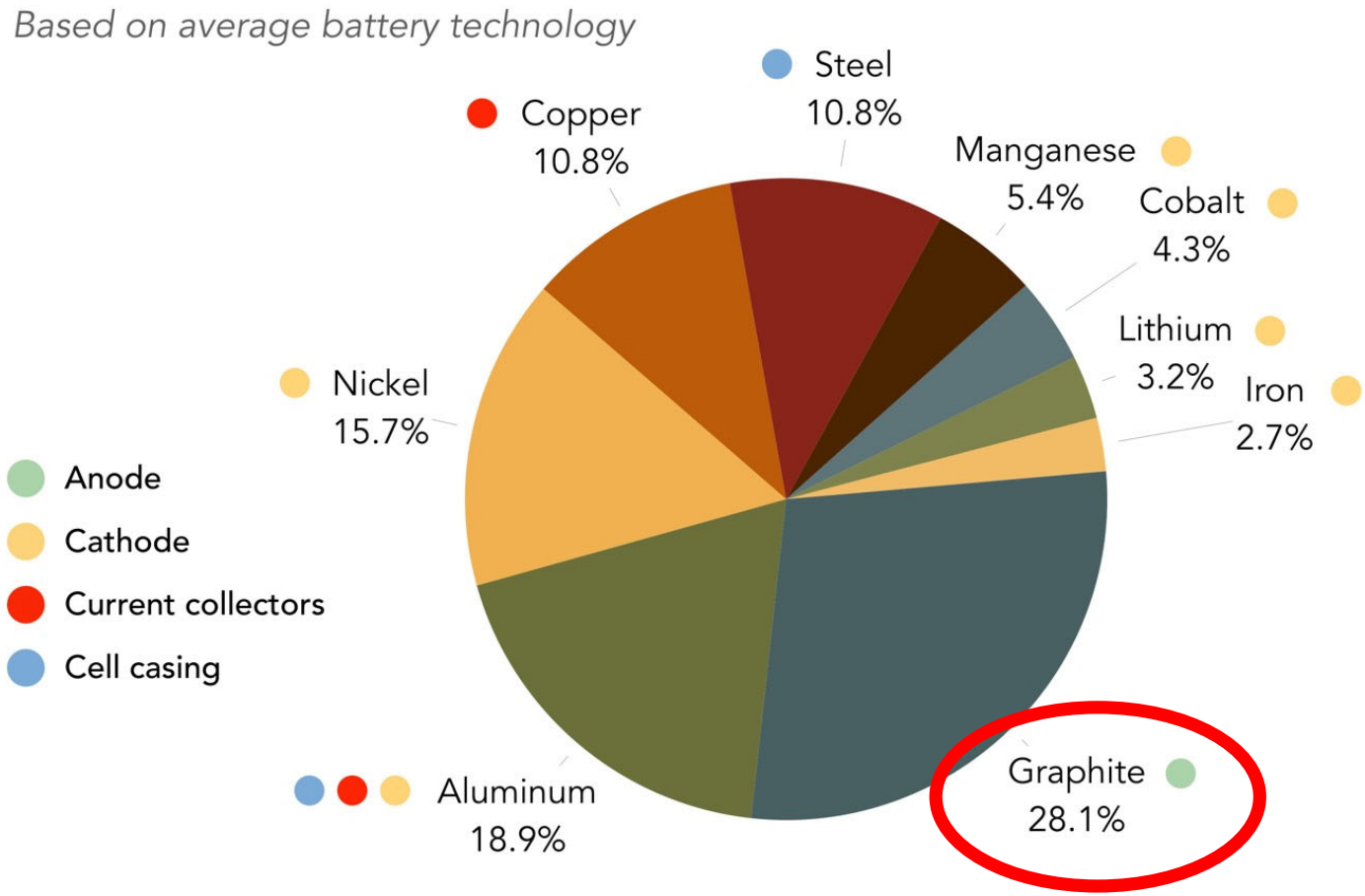
Lithium-Ion Batteries



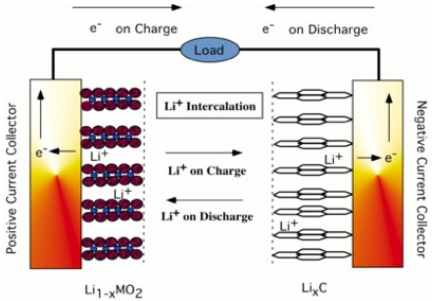


Lithium-Ion Battery Composition

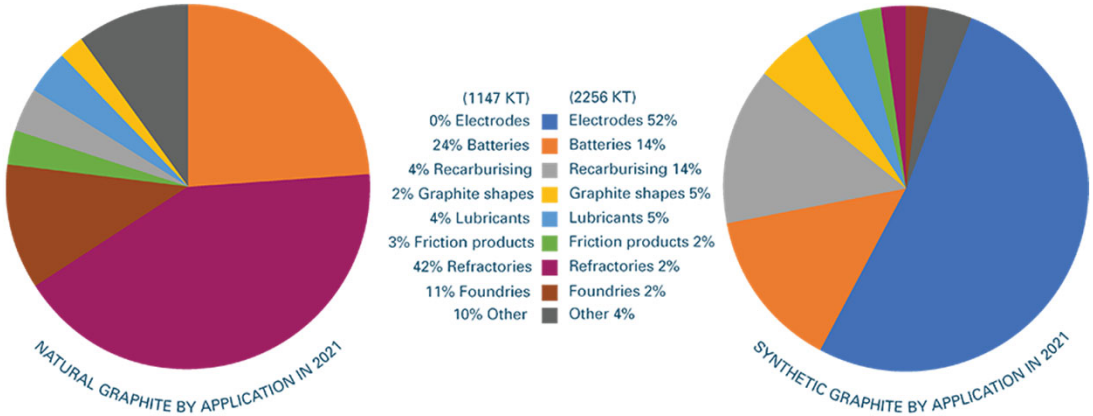


https://www-forbes-com.cdn.ampproject.org/c/s/www.forbes.com/sites/jimvinoski/2022/05/31/unless-we-get-serious-about-domestic-mining-americas-electrified-future-is-impossible/amp/

Graphite – Strategic Mineral



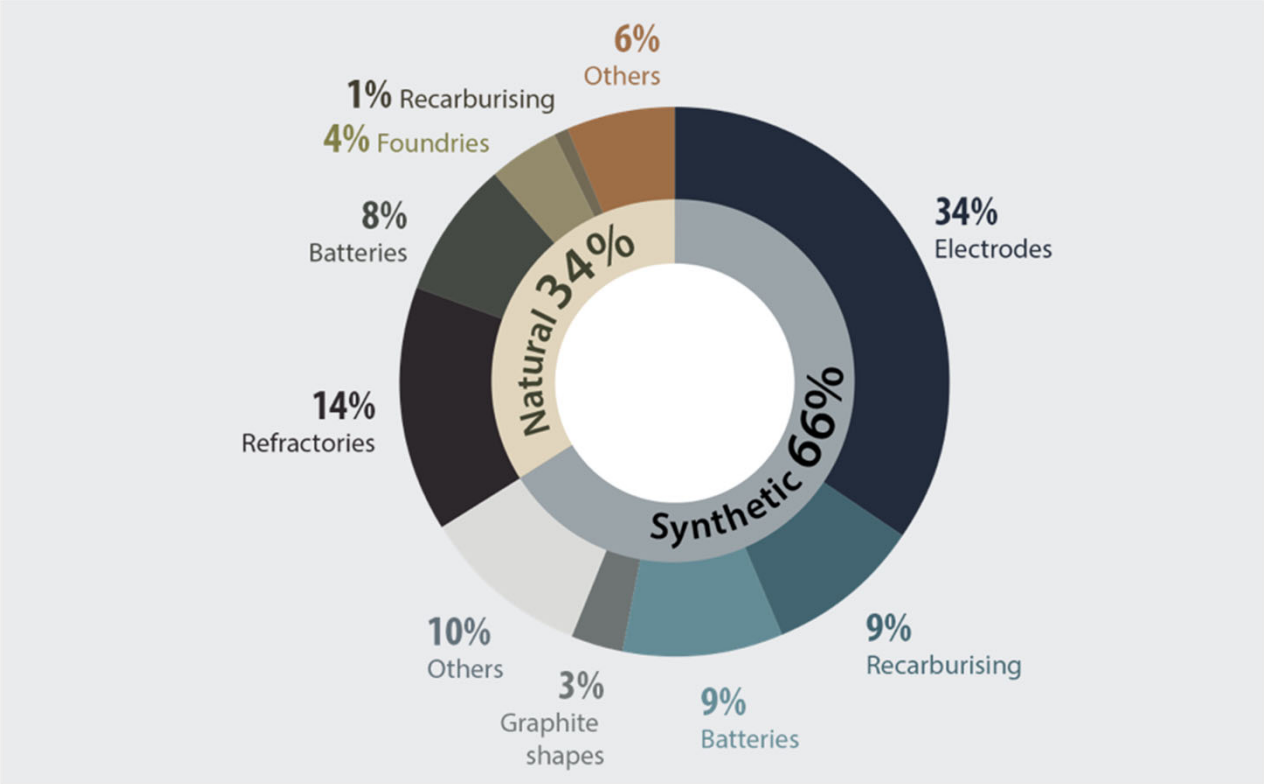
Adapted from: Sivakkumar, S. R.; Nerkar, J. Y.; Pandolfo, A. G., Rate capability of graphite materials as negative electrodes in lithium-ion capacitors. Electrochimica Acta 55, (9), 3330-3335.



source: Wood MacKenzie, 2022

Graphite Market

Graphite, global uses, 2021



~ 3.5 million tons/yr

Tesla Li-ion Battery Gigafactory

Gigafactory Proliferation

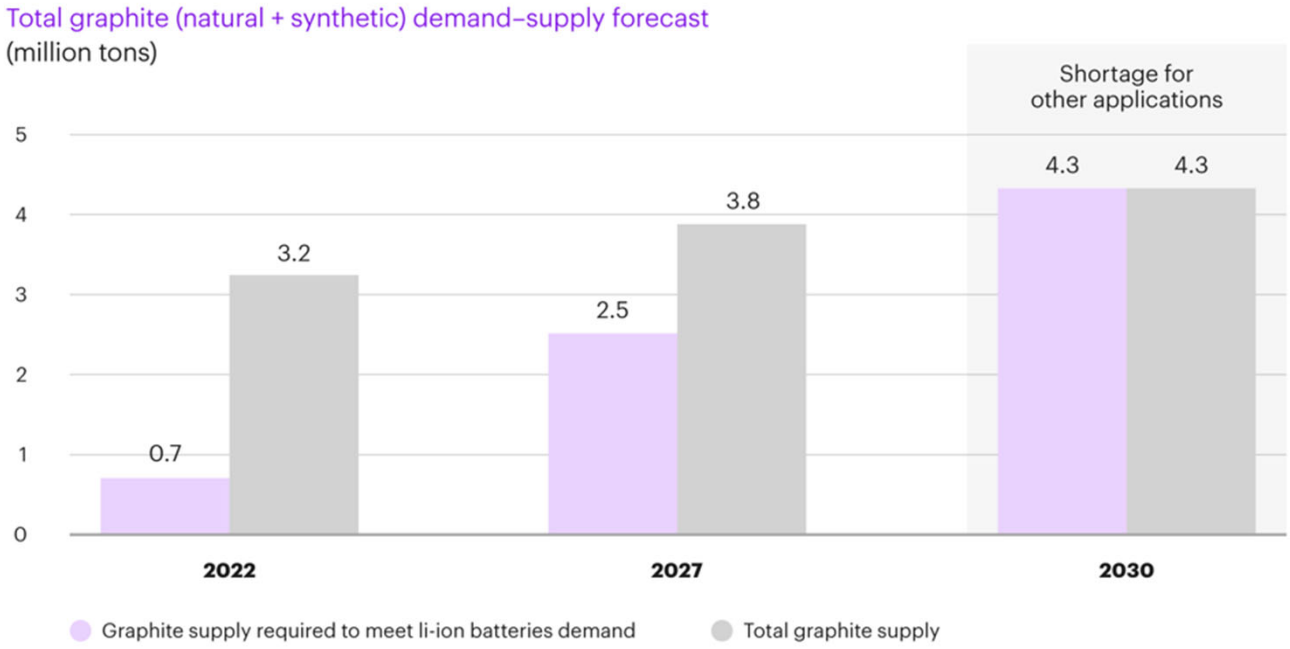
Gigafactories

Over 800 GWh of Planned Battery Production by 2025

EV Demand For Graphite

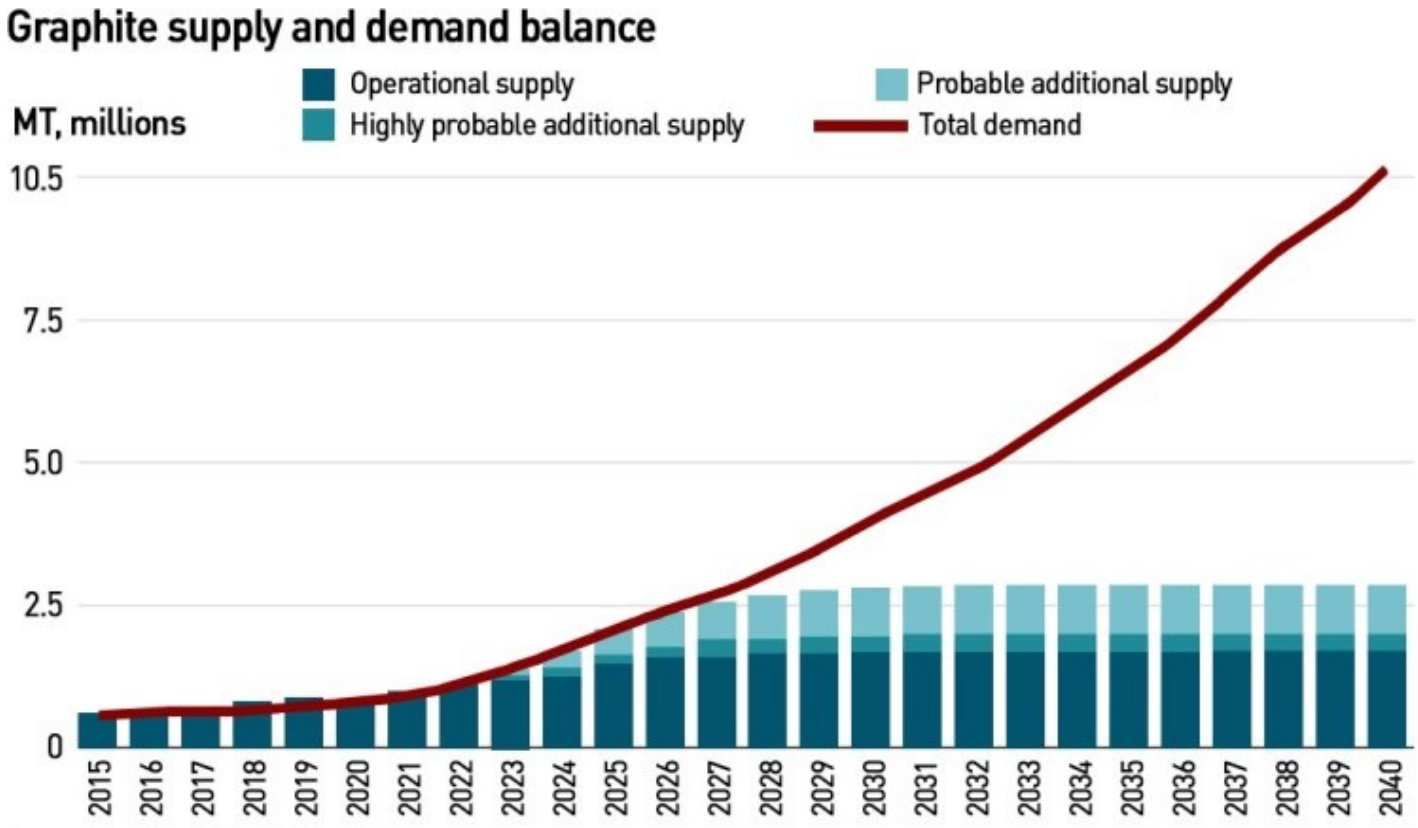
Figure 1

EV demand will absorb all graphite output at current rate



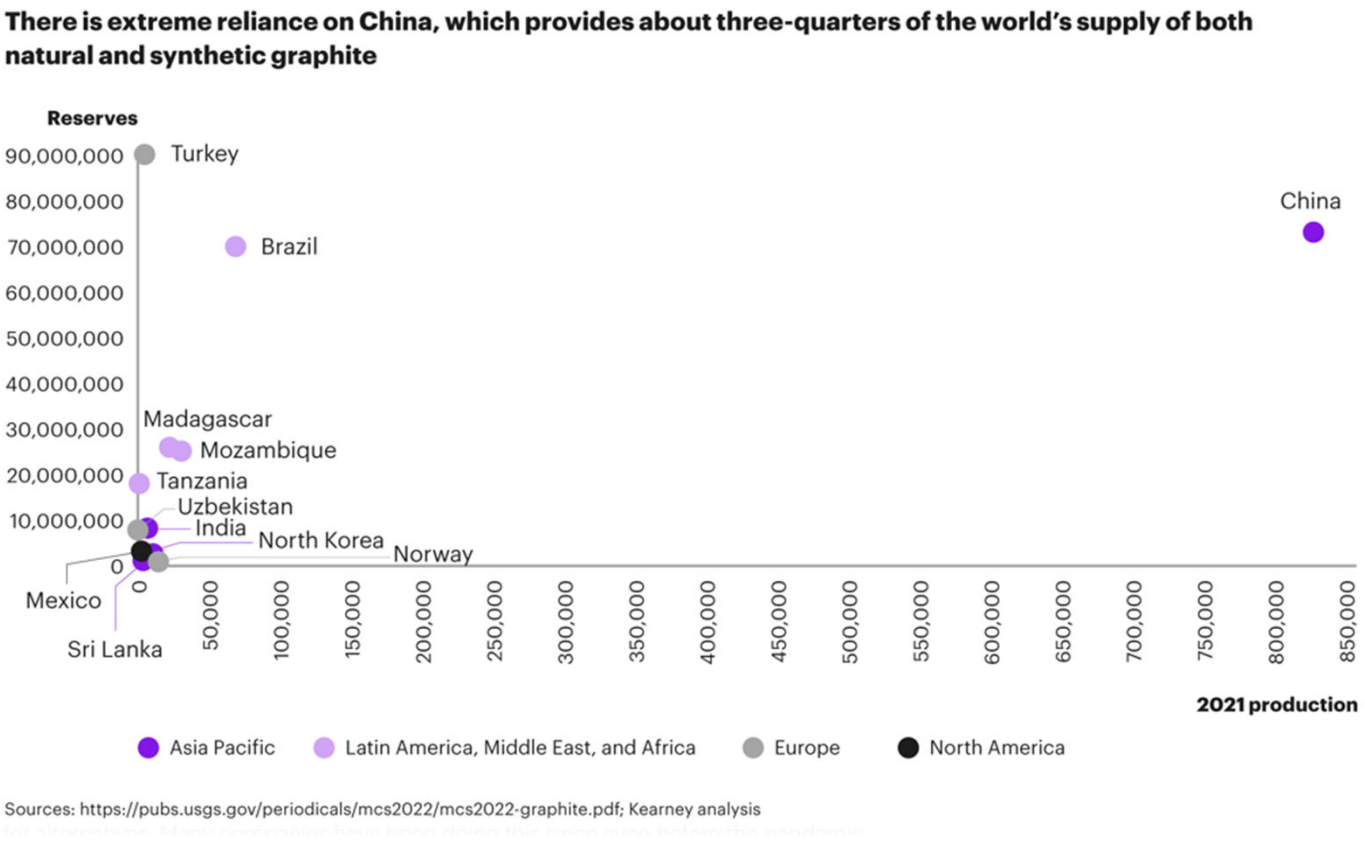
Sources: desktop research, expert interviews, supply from Allied Market Research, demand information from https://nmg.com/wp-content/uploads/2021/06/NMG-Graphite-101.pdf; Kearney analysis

EV Demand For Graphite



Benchmark Mineral Intelligence

Highly Concentrated Graphite Production



China produces ~ 99% of uncoated spherical Li-ion battery graphite

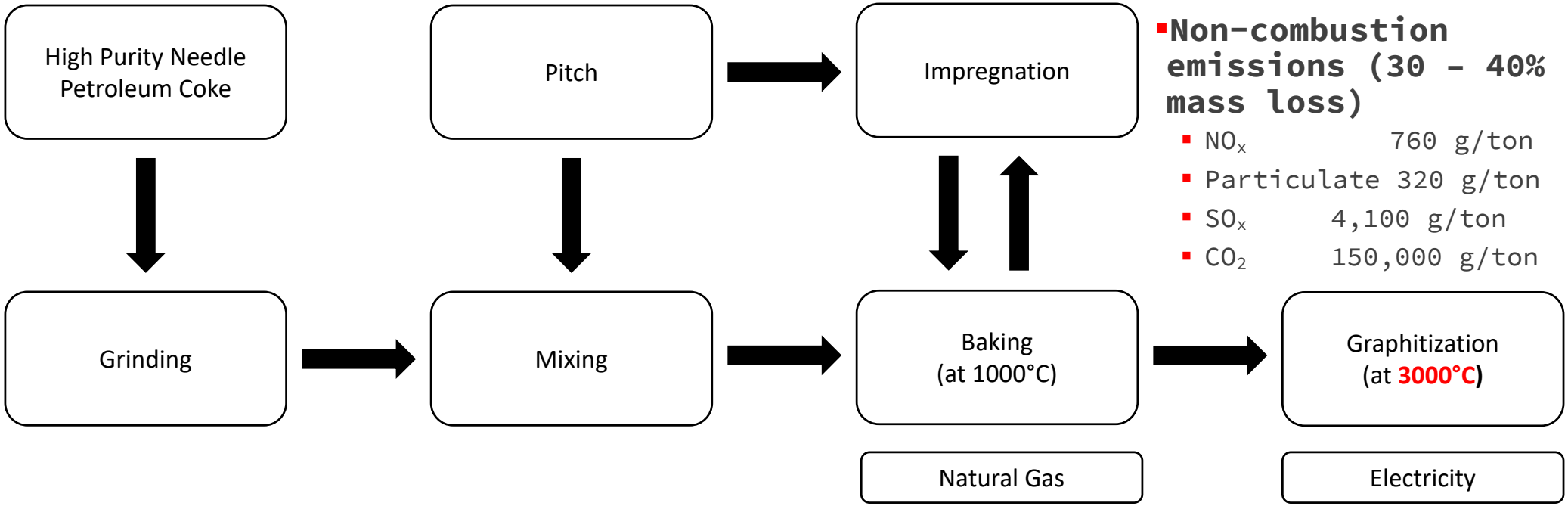
Graphite: Existing Supply & Production

Properties Needed for Battery Grade Graphite

- Purity (>99.9%C)
- Appropriate Crystallite Size (<10µm)
- High Crystallinity
- Appropriate Shape (Spherical, ~ 20 µm)
- Low Surface Area (< 4 m^2/g)

Graphite Supply - Synthetic

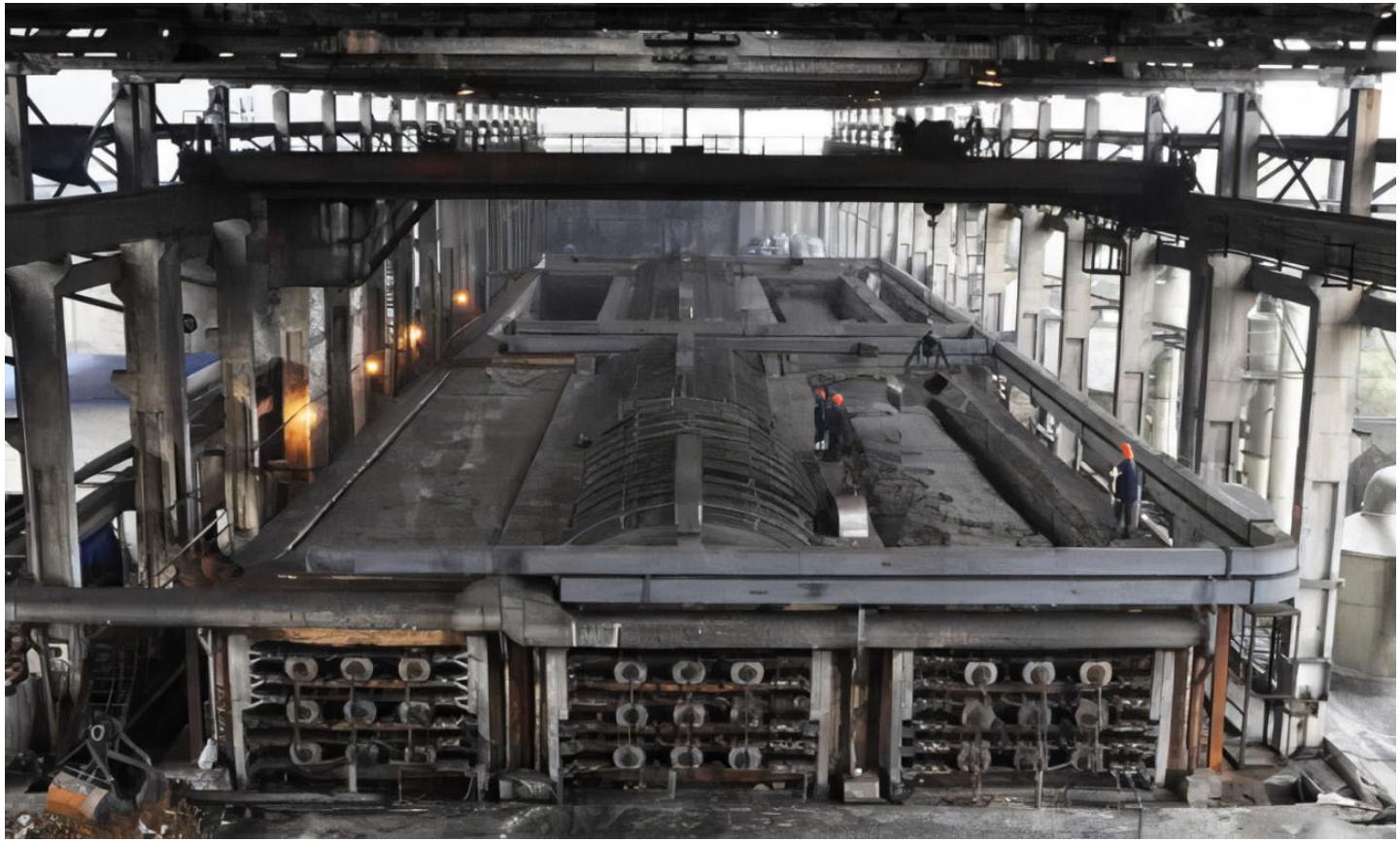
Fossil Fuel Based Precursors



- **Non-combustion emissions (30 – 40% mass loss)**
  - NO_x 760 g/ton
  - Particulate 320 g/ton
  - SO_x 4,100 g/ton
  - CO_2 150,000 g/ton

Weeks of Heating

Graphite Supply - Synthetic



> 7500 kWh/t

https://th.bing.com/th/id/R.6006b425cbeb07069549e83bffdd5f61?rik=sjpAk5o4OdNsIg&pid=ImgRaw&r=0&sres=1&sresct=1

Graphite Supply - Mining

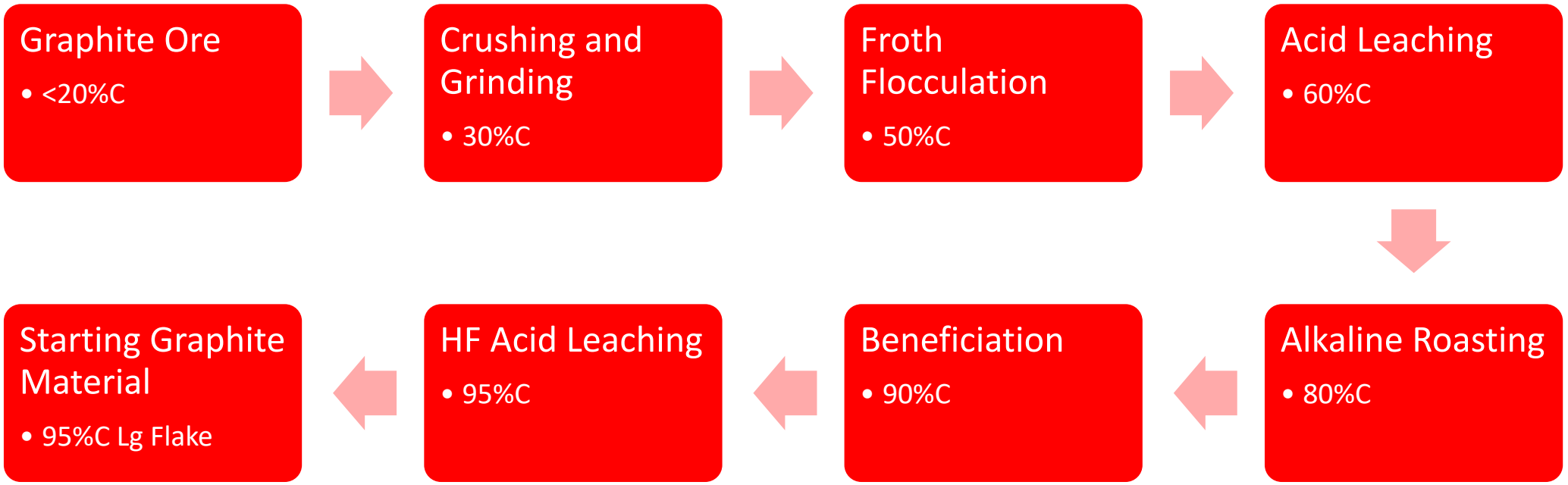
https://geology.com/minerals/graphite.shtml

Graphite Supply - Mining - Tanzania

Posco Future M Co. (Korea) contracted entire production

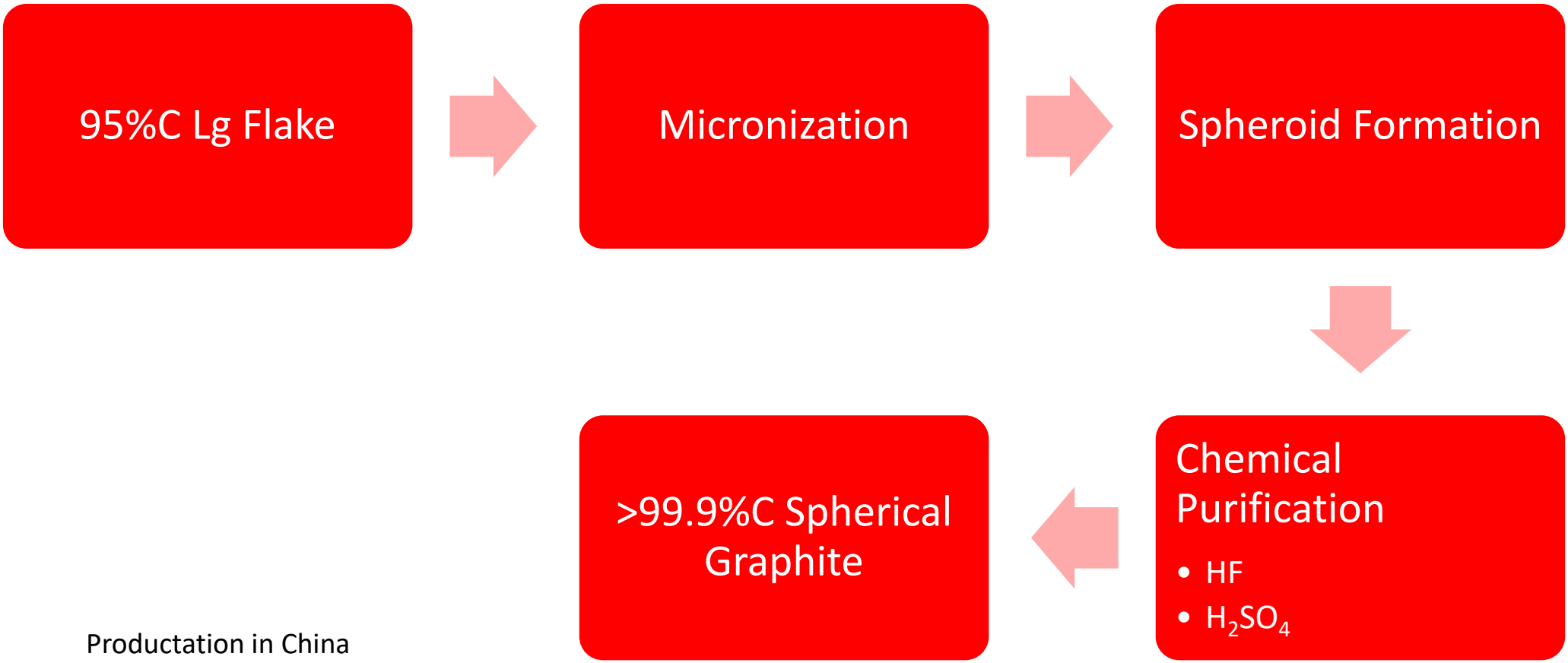
https://energycapitalpower.com/biggest-graphite-mines-africa-reserves/

Graphite Supply – Mining Purification



Mine production is typically 20 – 40% amorphous graphite – low value, inappropriate for Li-ion batteries

Micronization & Spheroidization



Productation in China

Graphite Supply – Processing Polution

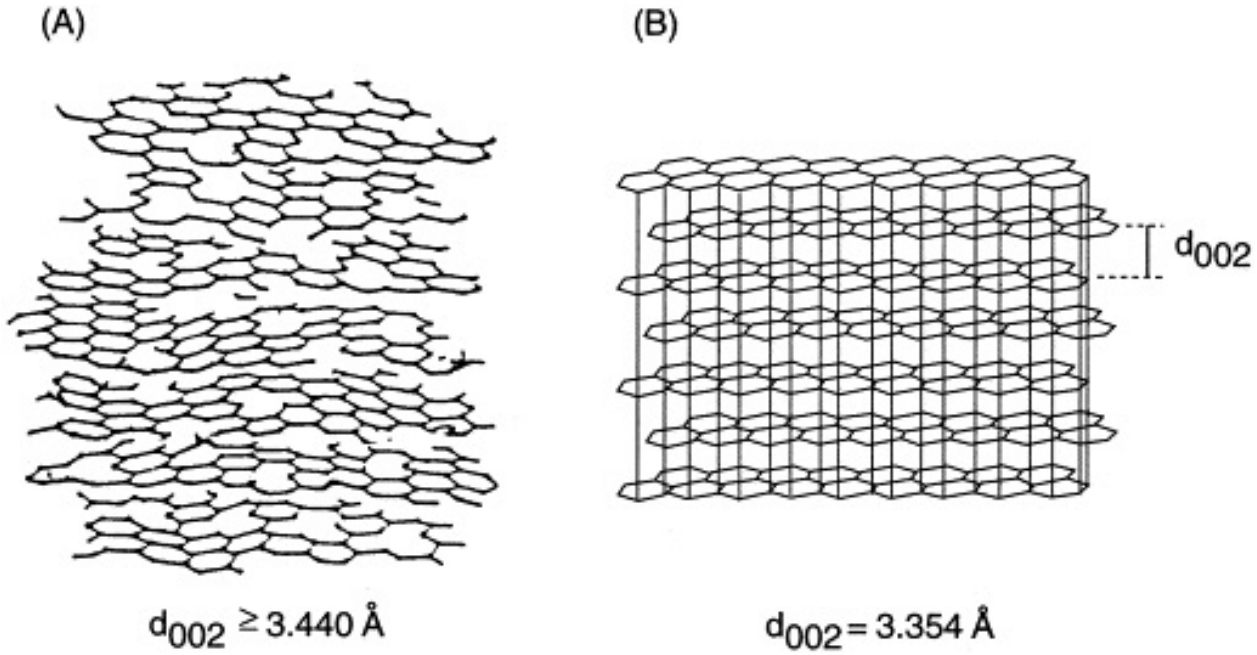
http://www.china.org.cn/environment/2014-04/28/content_32224052

Graphite Supply – Processing Polution

https://www.washingtonpost.com/graphics/business/batteries/graphite-mining-pollution-in-china/

Graphite Synthesis: Biomass

Synthesis from Non-Graphitizable Carbons



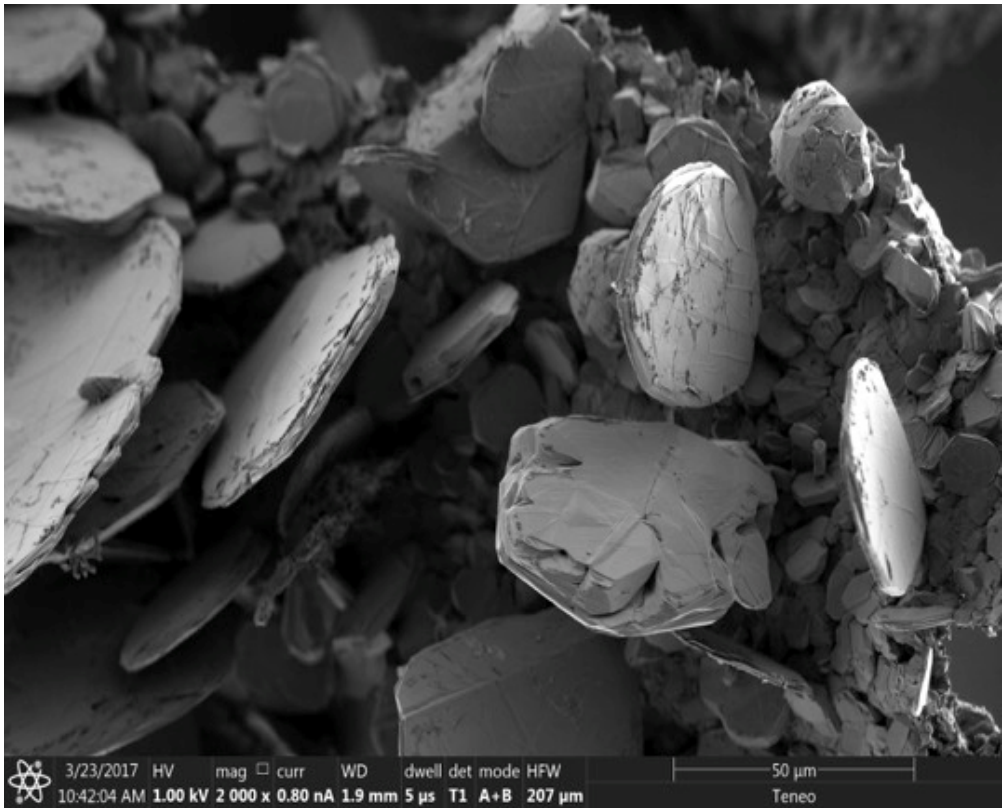
$d_{002} \geq 3.440$ Å

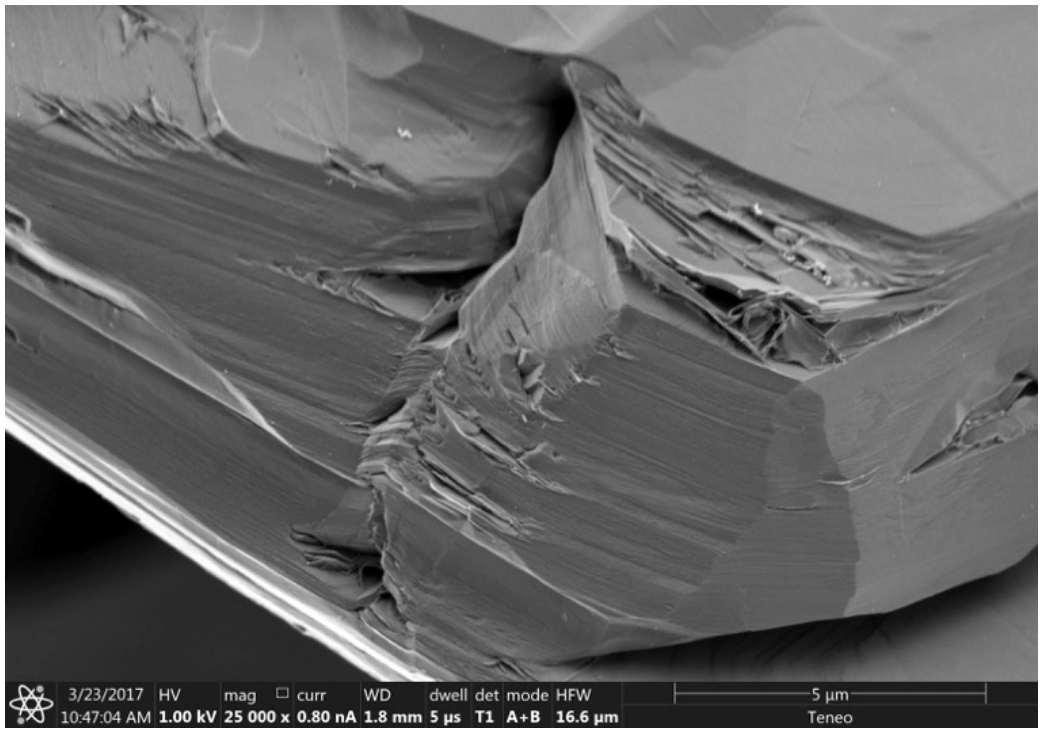
- Non-graphitizable
  - Biomass chars
  - Lignite & Anthracite

$d_{002} = 3.354$ Å

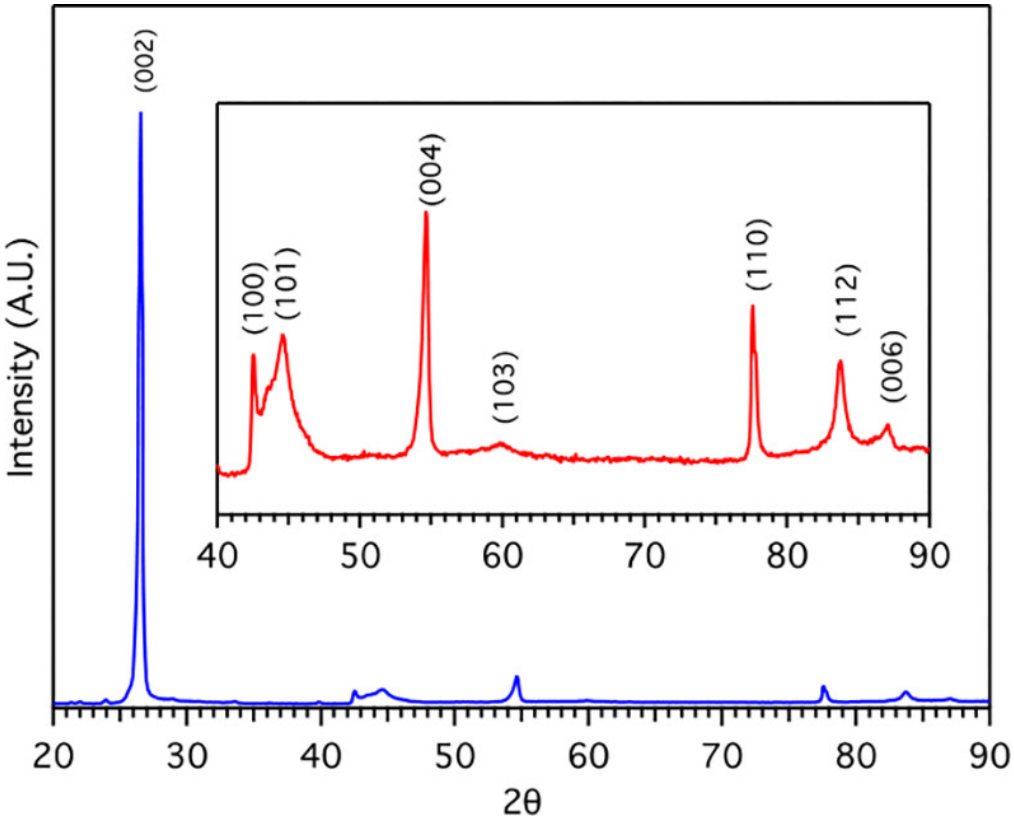
- Graphitizable
  - Coking carbons

Graphite from Biomass





XRD Analysis



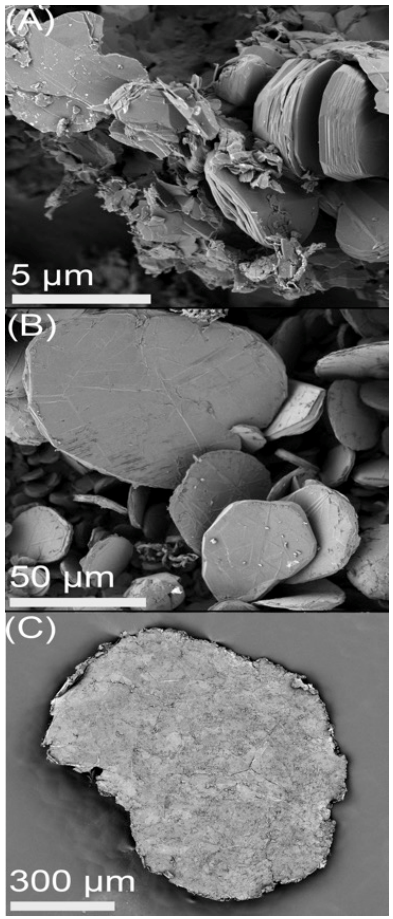
Degree of 3D Graphitic Order: >99.3%

Rational Flake Size Control

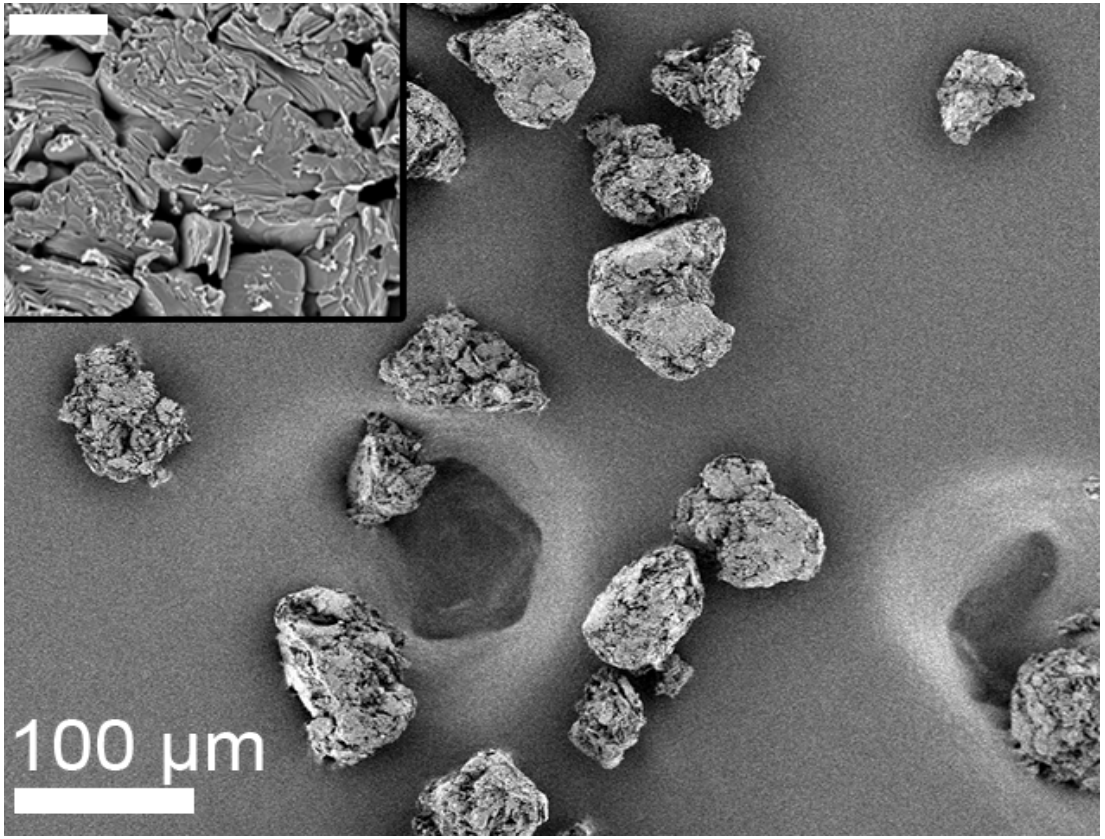
~5µm Fe

0.60mm Fe

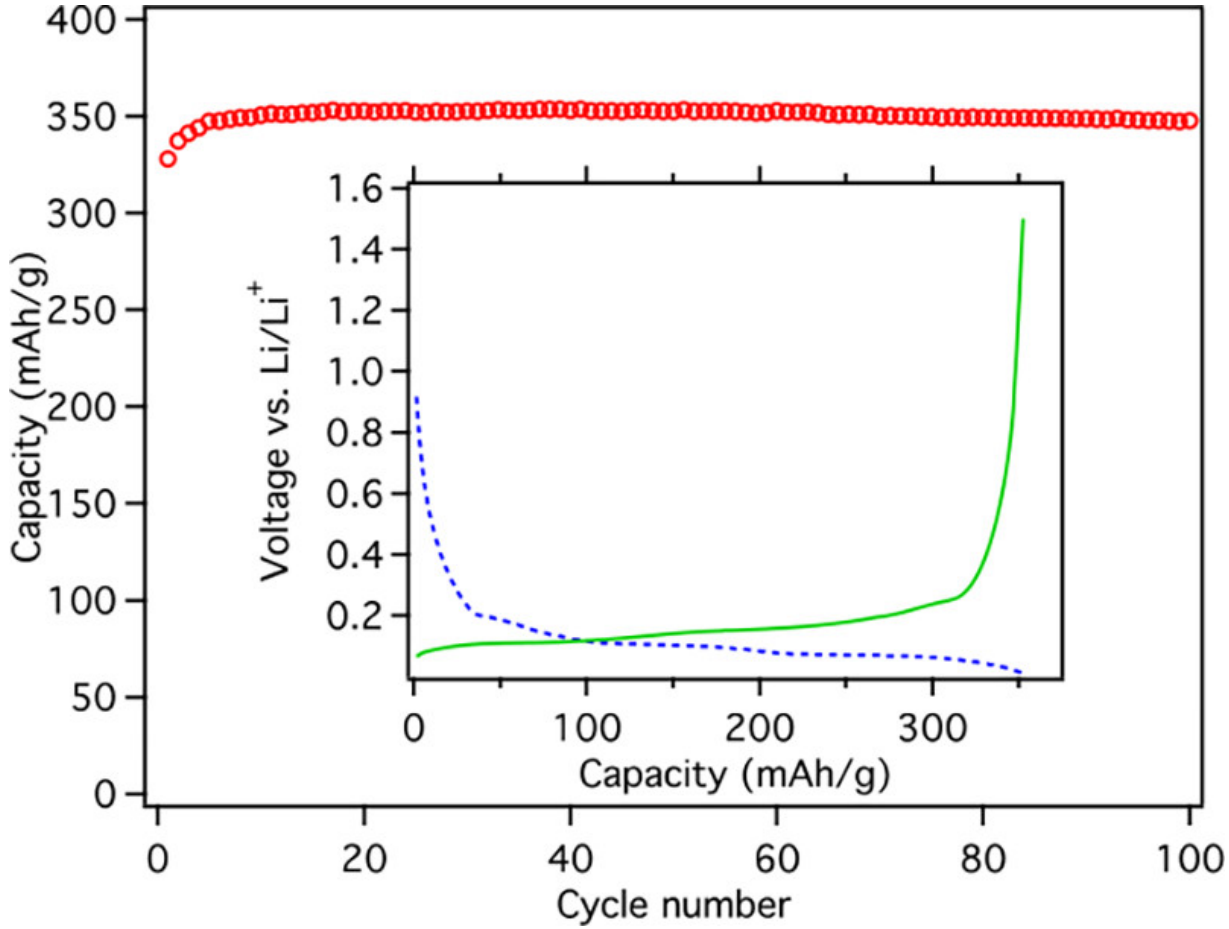
1–2mm Fe



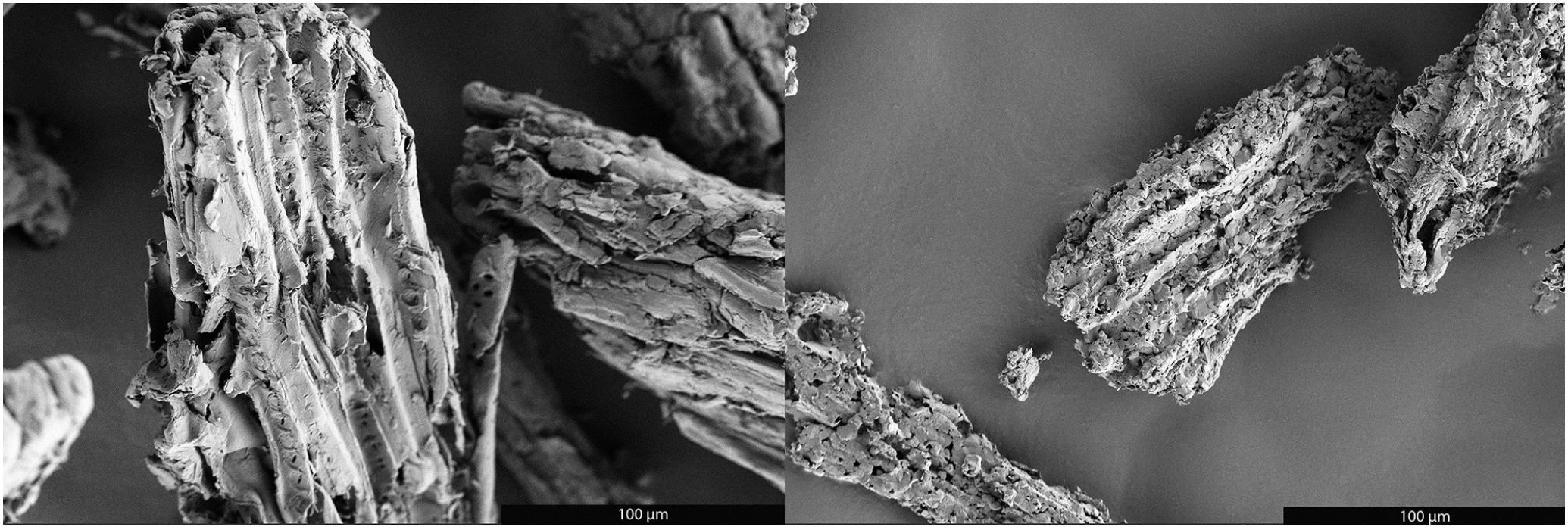
Spherical Graphite from Biomass



Battery Performance

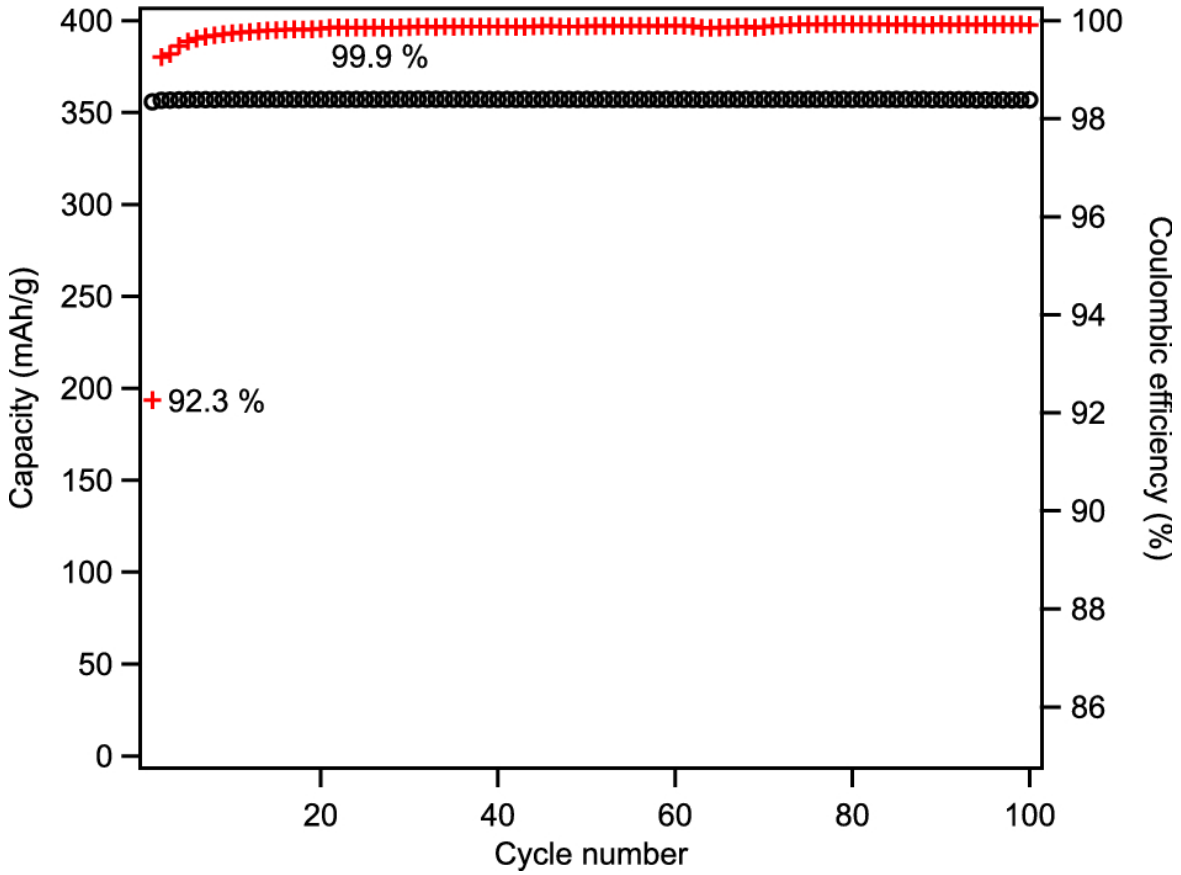


Wood Before and After Graphitization



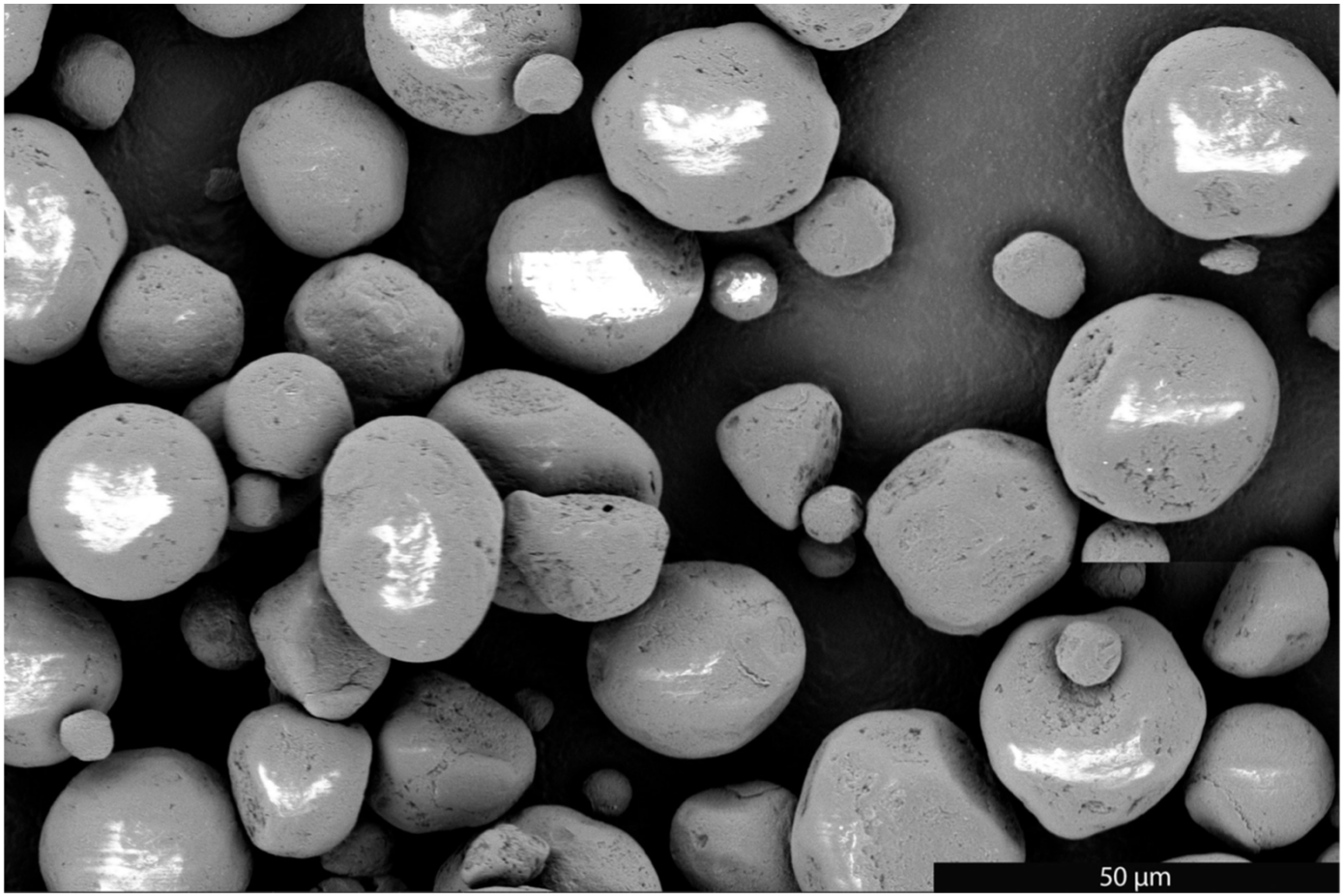
https://doi.org/10.1038/s41598-022-11853-x

Battery Performance



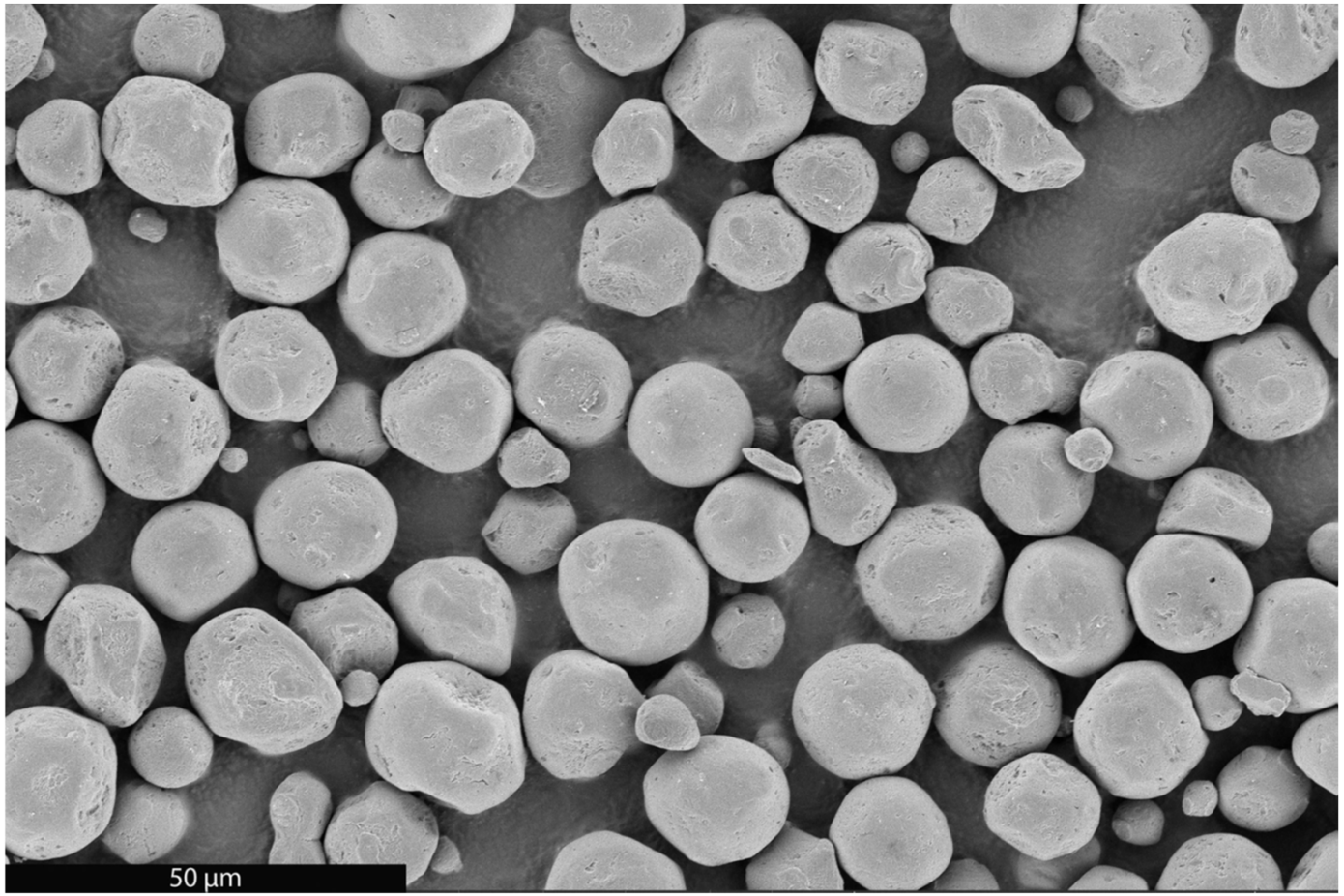
Rational Synthesis of Shaped Graphite

Cellulose Spheroids



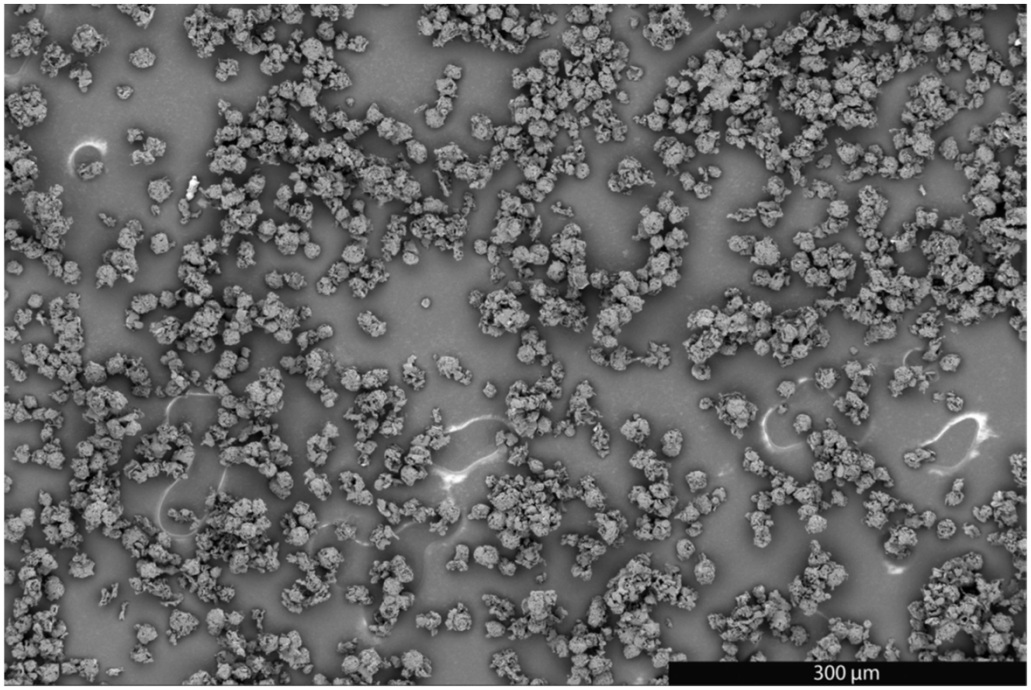
https://doi.org/10.1038/s41598-022-11853-x

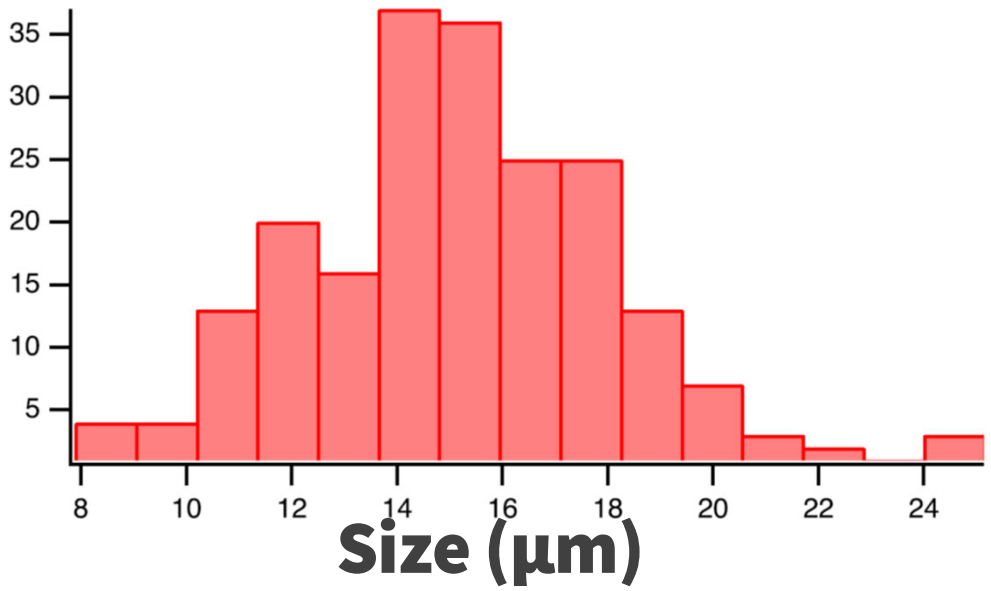
Cellulose Spheroid Char



https://doi.org/10.1038/s41598-022-11853-x

Spherical By Design

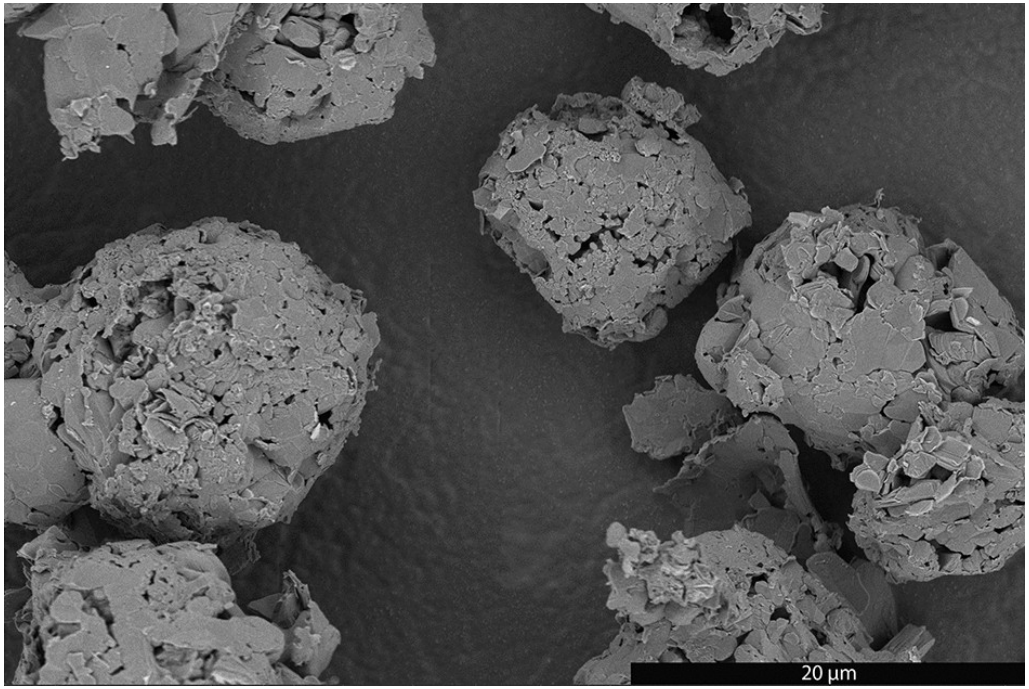




https://doi.org/10.1038/s41598-022-11853-x

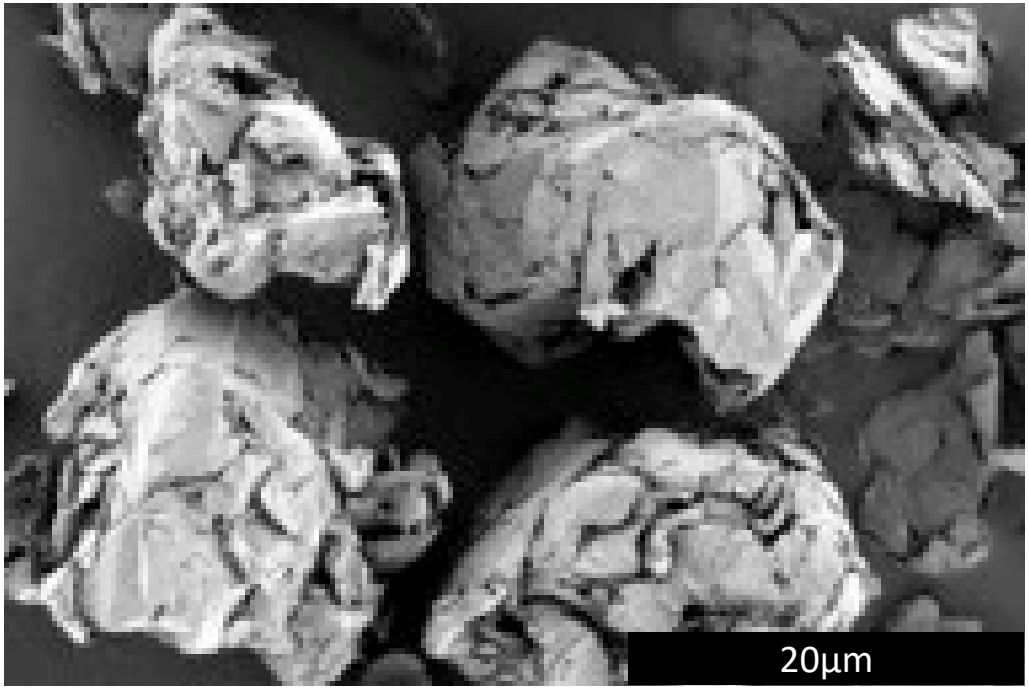
Spherical By Design

BIOMASS GRAPHITE



3.08 m^2/g

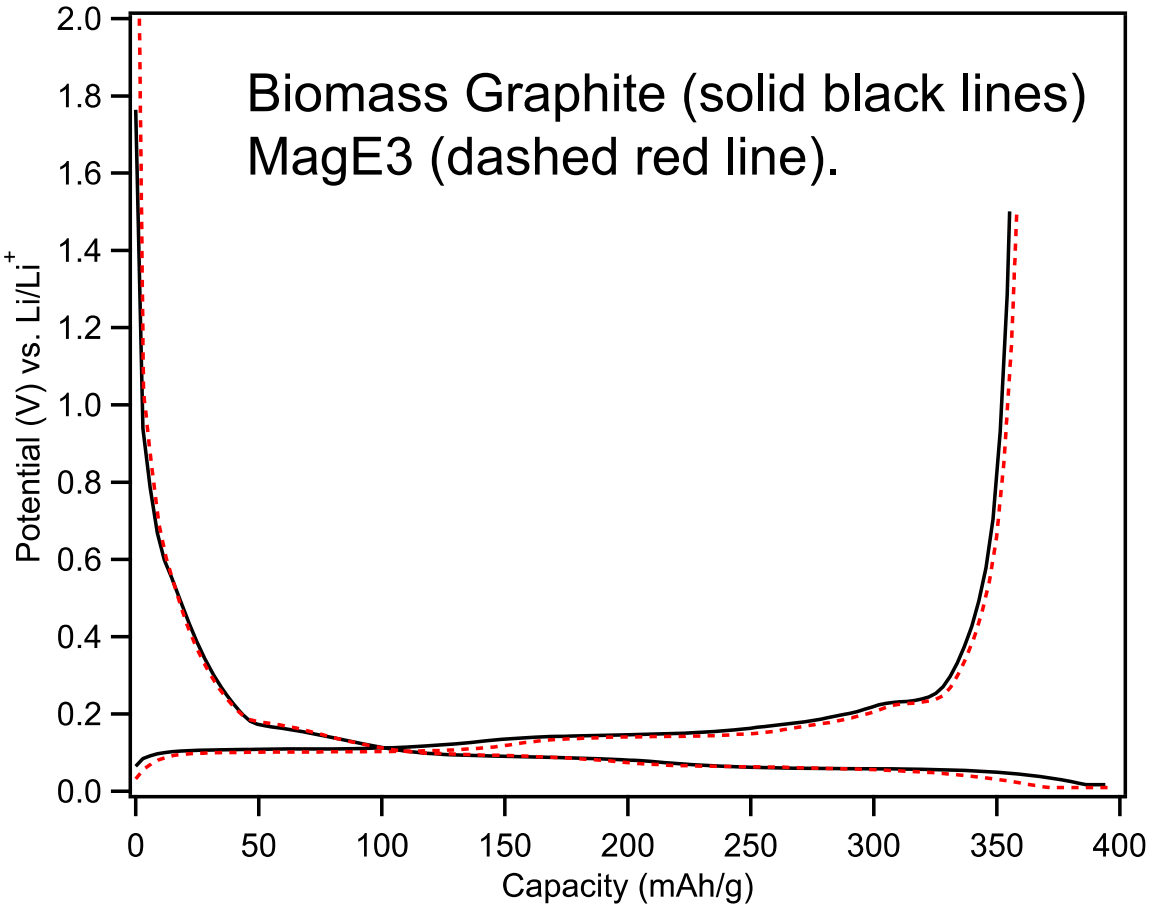
HITACHI MAGE3 (COMMERCIAL GRAPHITE)



2.83 m^2/g

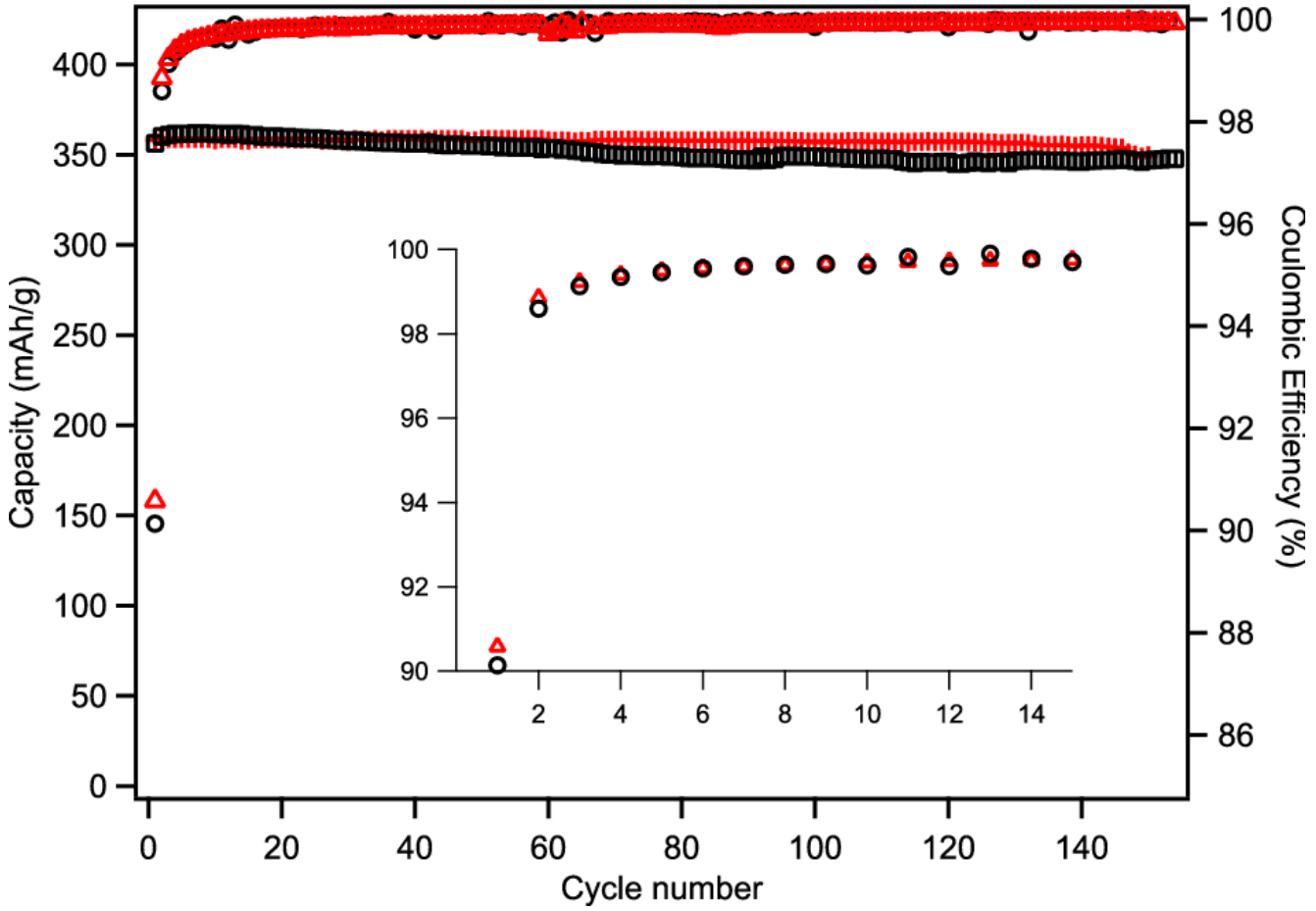
https://doi.org/10.1038/s41598-022-11853-x

Industrially Competitive Battery Graphite



https://doi.org/10.1038/s41598-022-11853-x

Cycle Life Comparison



https://doi.org/10.1038/s41598-022-11853-x

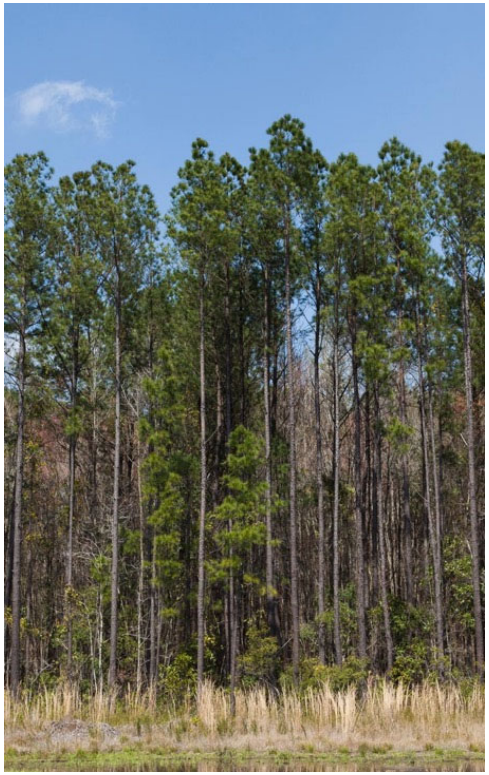
Graphite from Biomass

- High Purity (>99.95%)
- Efficient Carbon Conversion (>95.7%C)
- Energy Efficient (0.61 kG/KWh)
- Shape and Flake Size Control
- Low Surface Area Possible
- 90.2% 1st CE (Commercial ~90%)
- High Capacity (>355 mAh/g)
- Excellent cycle life
- Market Disruptive Production Cost?

Waste Biomass

AGRICULTURE

FORESTRY

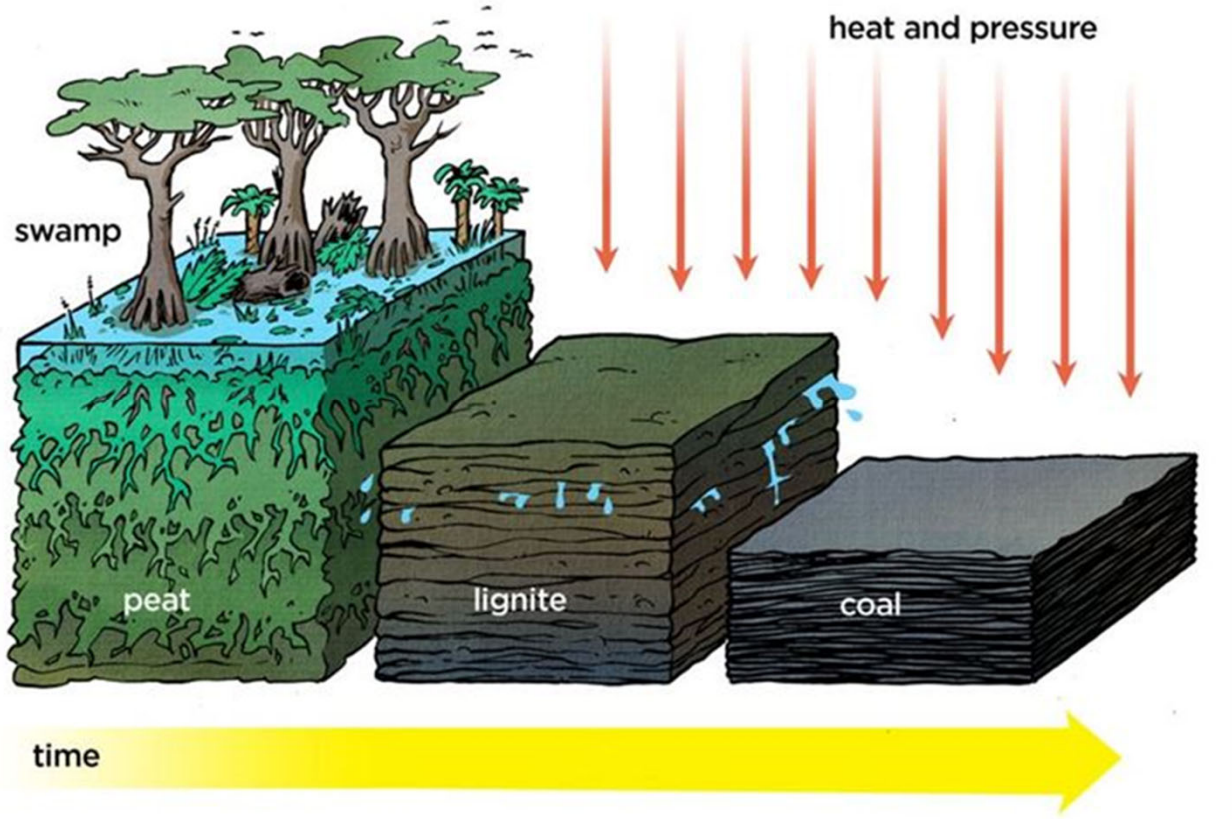


Corn Stover

Wood Pellet Production

Sourcing radius ~ 75 miles

Geologically Concentrated Biomass



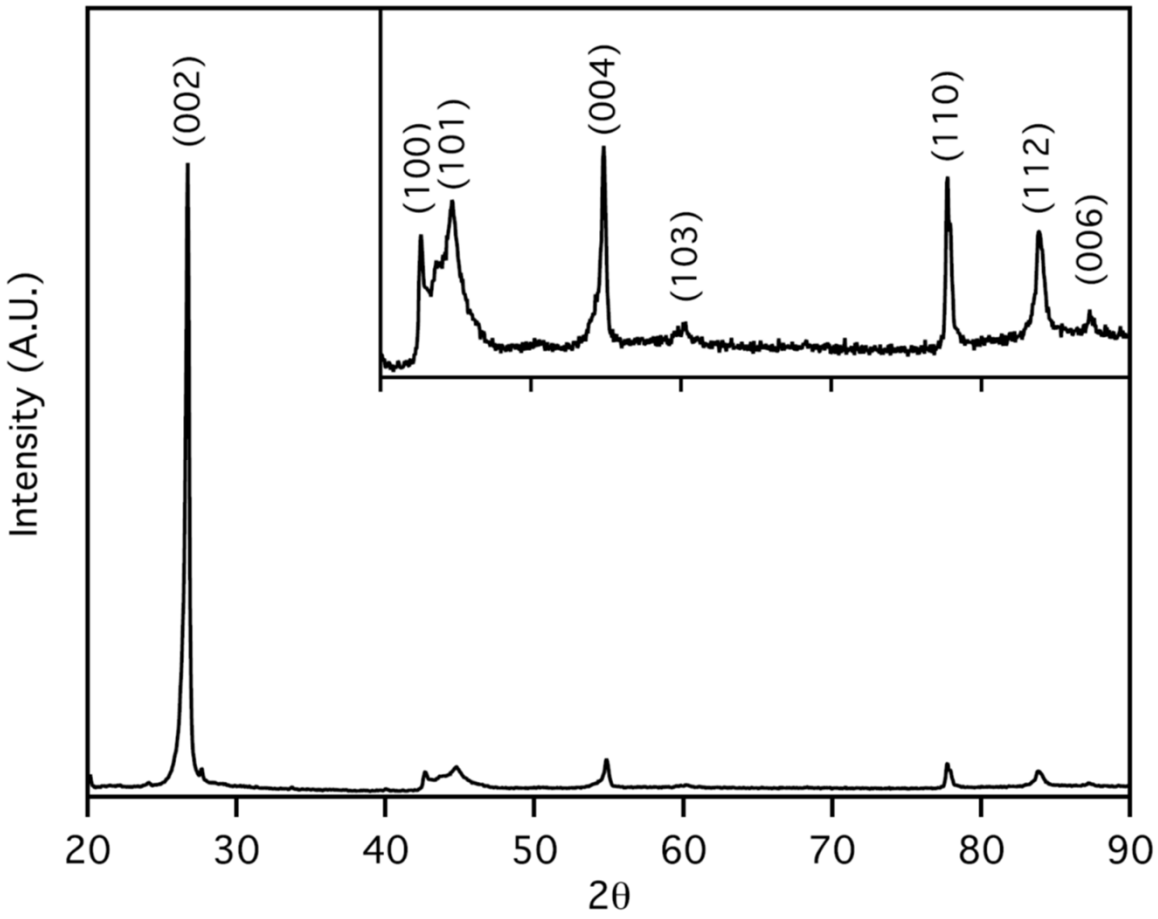
Lignite - Carbon Ore

Graphite Synthesis: Lignite

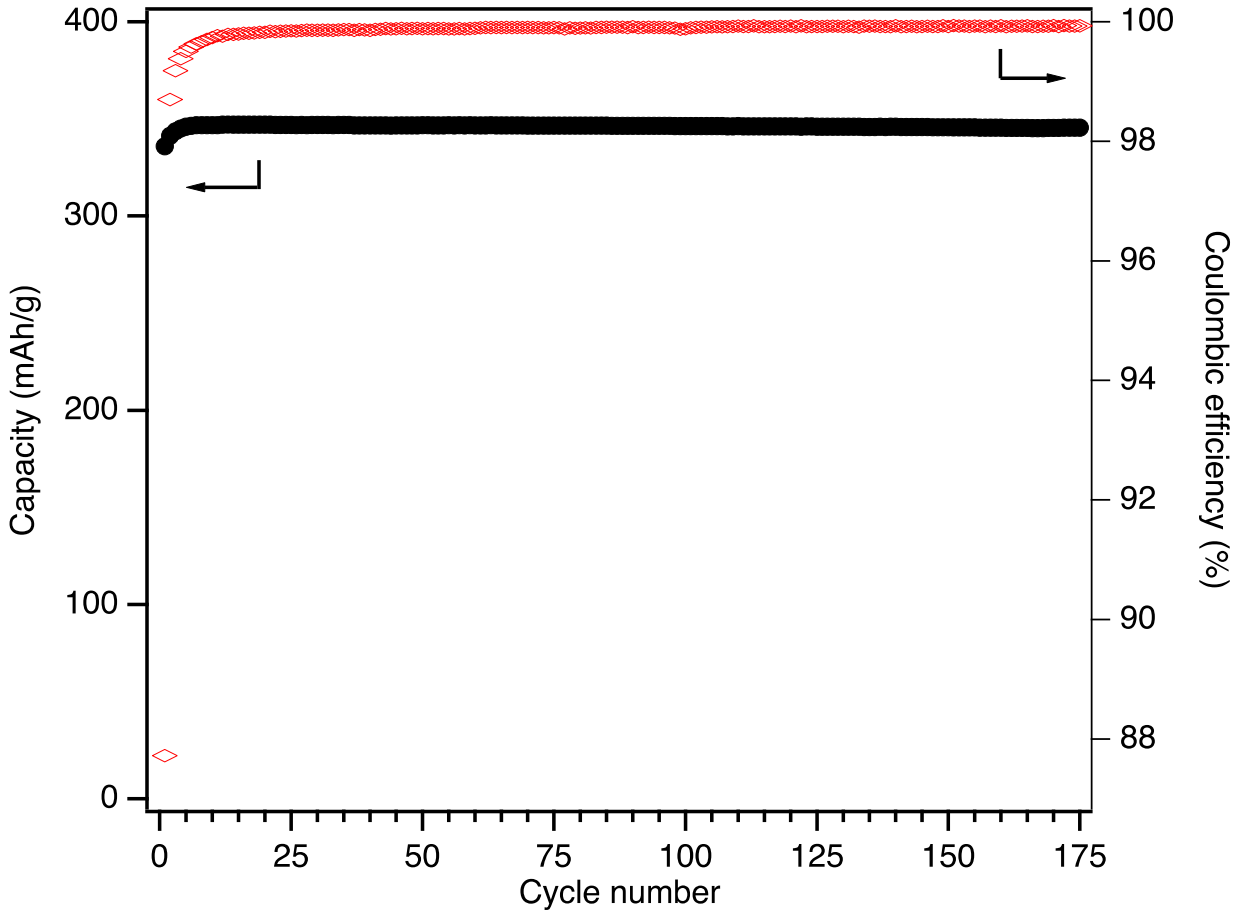
Why Lignite?

- Naturally abundant
- High carbon concentration
- Established supply chain
- Minimize Transportation
- Inexpensive

Graphite From Lignite



Graphite From Lignite - Li-Ion Battery



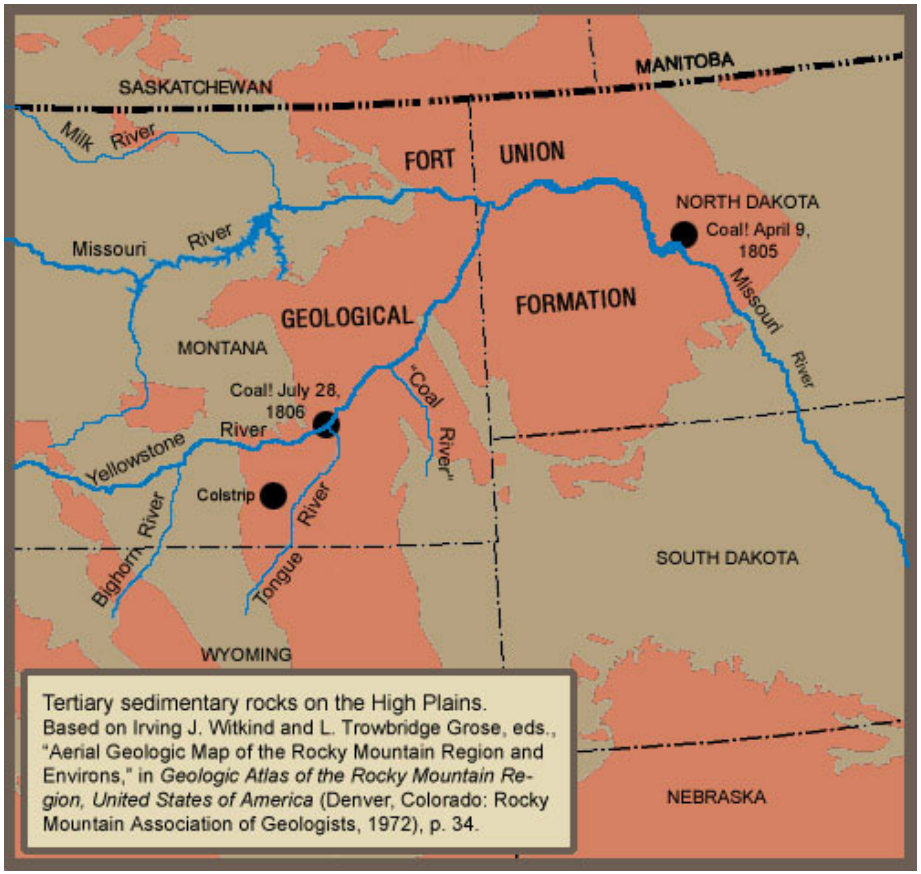
Graphite From Coal: Battery Performance

- Commercially viable capacity (347 mAh/g)
- Good capacity retention and Coulombic efficiency

https://www.wesa.fm/post/new-coal-mine-opening-pennsylvania-trump-thank#stream/0

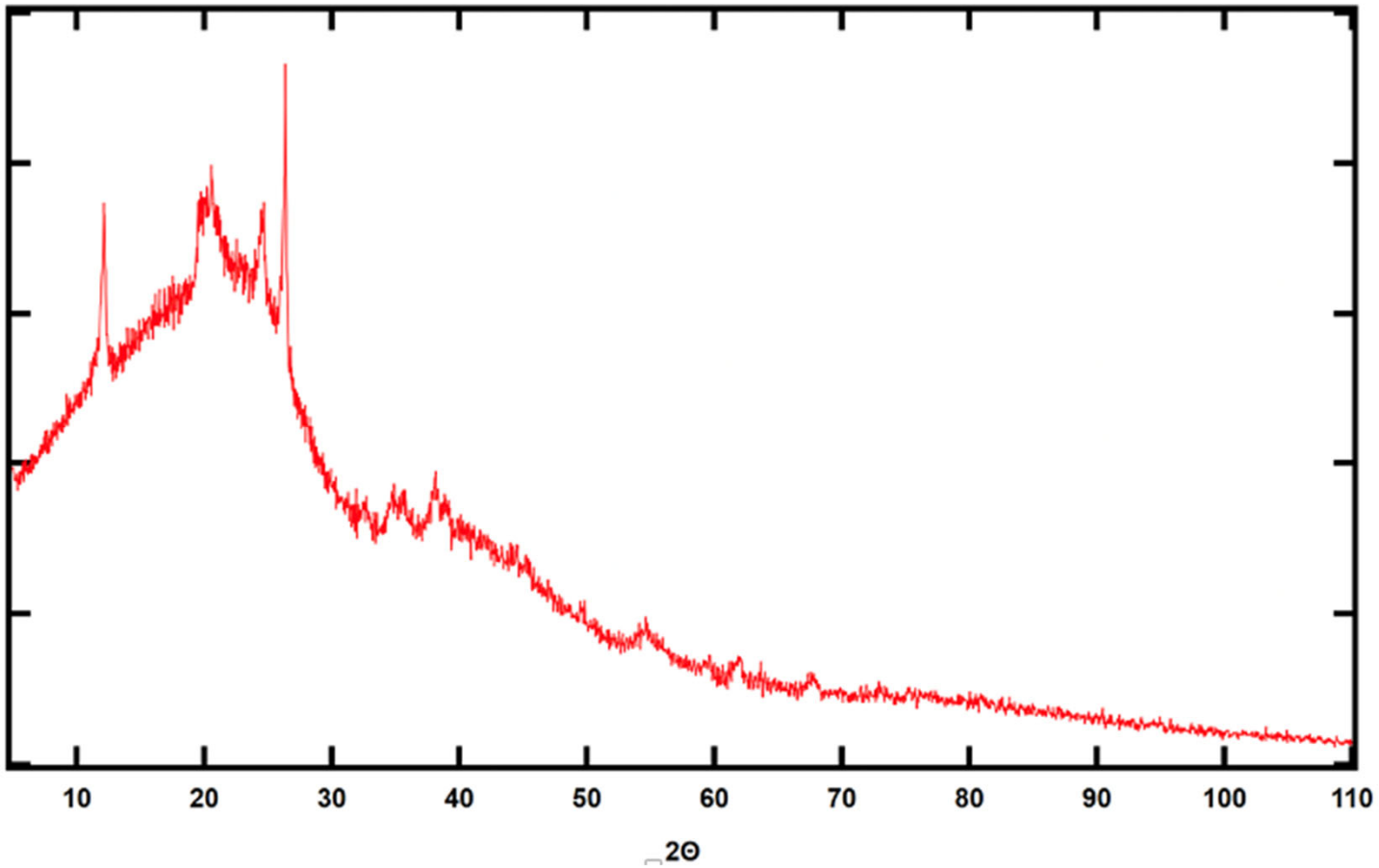
Graphite Synthesis: Estevan Lignite

Estevan – Fort Union Formation

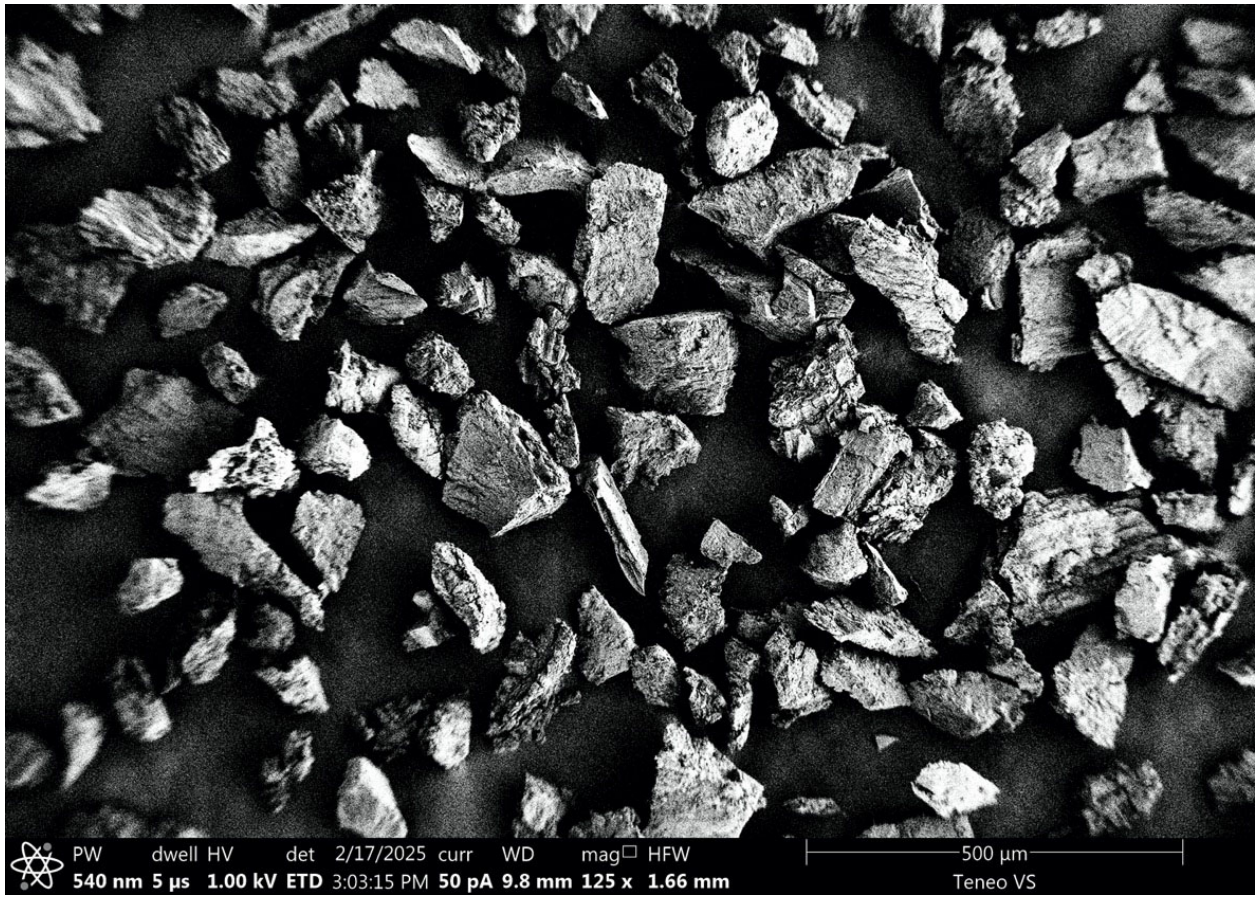


Tertiary sedimentary rocks on the High Plains.
Based on Irving J. Witkind and L. Trowbridge Grose, eds., "Aerial Geologic Map of the Rocky Mountain Region and Environs," in *Geologic Atlas of the Rocky Mountain Region, United States of America* (Denver, Colorado: Rocky Mountain Association of Geologists, 1972), p. 34.

Estevan Lignite – Clays and Silica

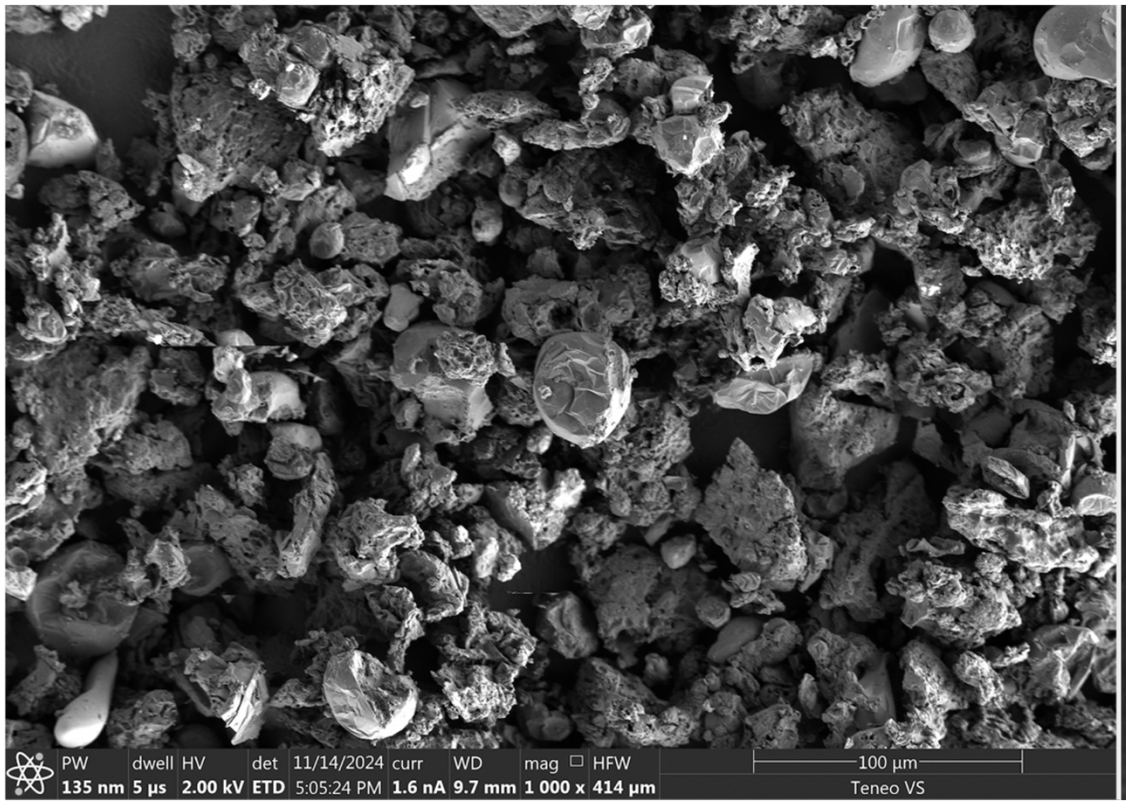


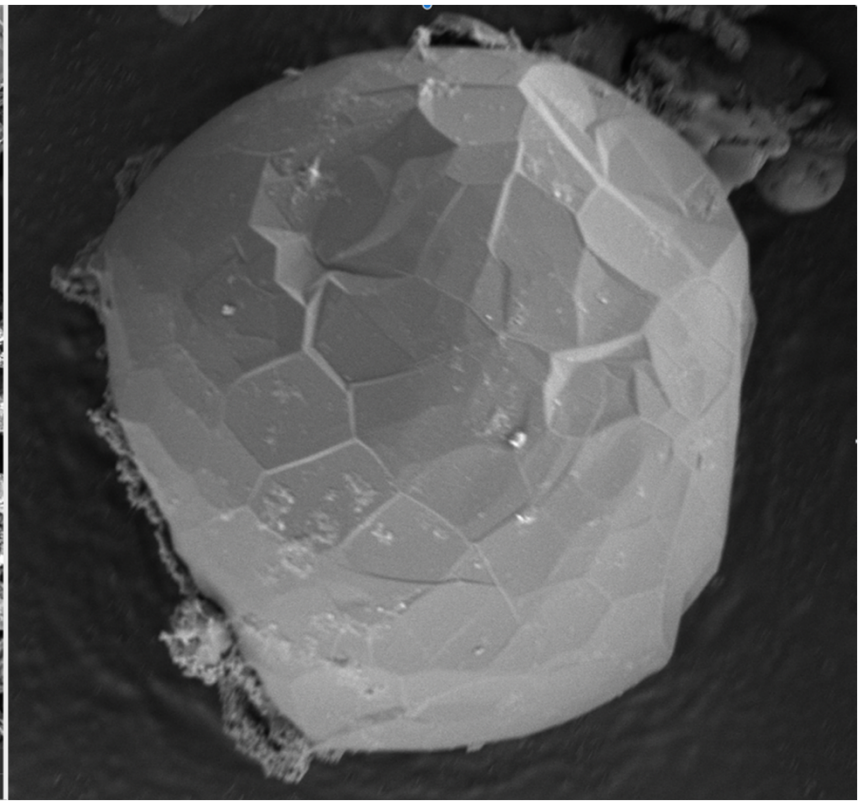
Estevan Lignite - Graphite



Estevan Lignite - Graphite

Estevan Lignite – Shaped Graphite



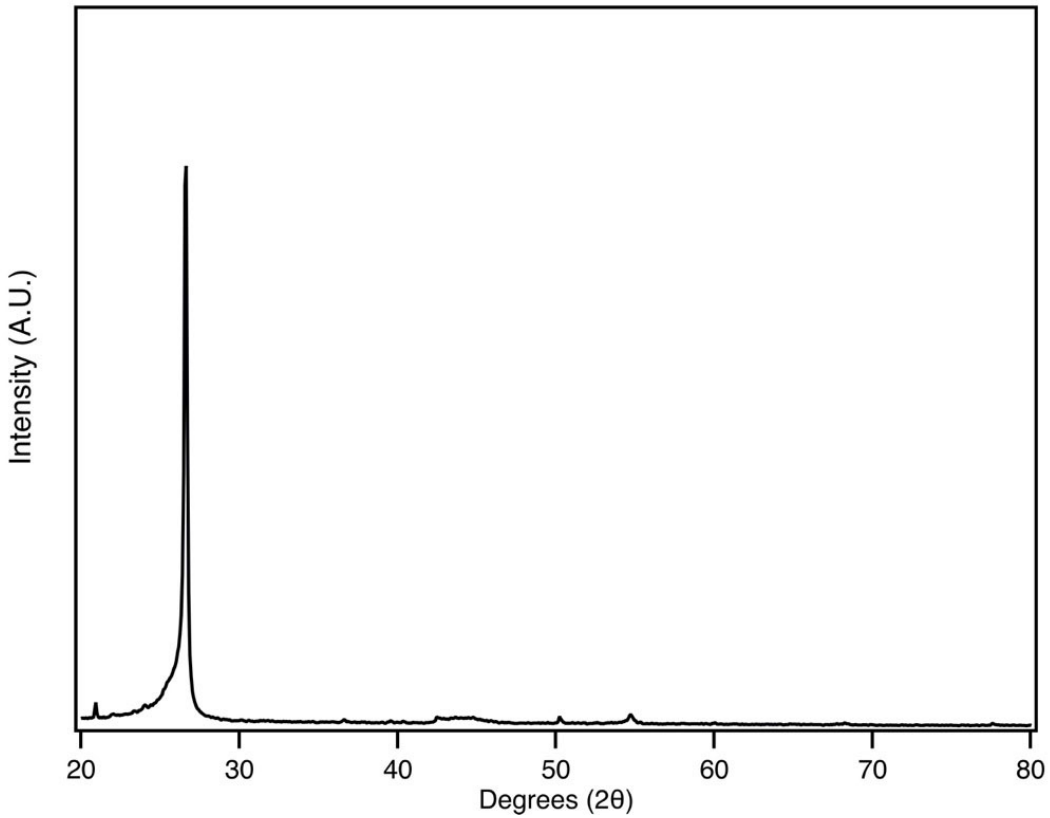


> 99.9 % C after purification

Estevan Lignite – Reactor Module

- Full-scale testing in lab
- Minimize scale-up technological risk
- Basis for techno economic analysis
- Provide quantities needed for qualification
- Scale by replication to pilot and production

Estevan Lignite - Graphite



Estevan Lignite – Li-ion Battery Graphite

- Reactor module with 12 kW laser
- Efficiency more than doubled
- Energy Usage 800 - 1600 kWh/ton (10 – 20% of current synthetic graphitization)
- Module production > 80 tonnes graphite/y
- Heat recovery charring – net electricity production
- Direct production of Li-ion battery grade “spherical” graphite
- Production costs – potentially disruptive

Estevan Lignite – Li-ion Battery Graphite

Dr. Kevin McKenzie

Dr. Nate Banek

Michael Scarberry

Jack Poland

Adrian Wood

Zach Weeks

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